Measurements of Temperature Sensitivity for Eight Aanderaa Pressure Gauges Fitted with Paroscientific Transducers

Jon Moen

Atlantic Oceanographic Laboratory
Ocean Science and Surveys, Atlantic
Department of Fisheries and Oceans

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

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Jon Moen

Atlantic Oceanographic Laboratory
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Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

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ABSTRACT

Moen, J. 1985. Measurements of temperature sensitivity for eight Aanderaa pressure gauges fitted with paroscientific transducers. Can. Tech. Rep. Hydrogr. Ocean Sci.:ix + 66 p.

Temperature sensitivity estimates are presented for eight Aanderaa pressure gauges (with Paroscientific pressure sensors) deployed to measure bottom pressure on the Newfoundland Grand Banks during the winter and spring of 1984. The sensitivies, ranging from -2 to +2 mbar/°C, are found to depend strongly on both pressure and temperature, and to vary between gauges.

It is shown that even for the very low variability in temperature (standard deviation approx. 0.5°C) found in the Grand Banks data, temperature can significantly affect pressure variance causing discrepancies of typically less than 10%, but in a few 'worst' cases of over 30%, for the low frequency (2 to 10 day) bands.

Clearly, in areas of higher temperature variability these temperature effects could be even larger, particularly at low frequencies of the pressure variance spectrum.

RESUMÉ

Moen, J. 1985. Measurements of temperature sensitivity for eight Aanderaa pressure gauges fitted with paroscientific transducers. Can. Tech. Rep. Hydrogr. Ocean Sci.:ix + 66 p.

On présente des estimations de la sensibilité thermique de huit manomètres Aanderaa (avec capteurs de pression Paroscientific) déployés pour mesurer la pression sur les Grands bancs terre-neuviens à l'hiver et au printemps 1984. La sensibilité variant de -2 à -2 mbar/°C dépend fortement de la pression et de la température, et varie d'un manomètre à l'autre.

Même si on a noté de très faibles variations de température (écart-type 0,5°C environ) sur les Grands bancs, cette variable peut contribuer beaucoup aux variations de pression qui causent des erreurs de mesure de moins de 10% en général, mais de plus de 30% dans les "pires cas", pour les bandes de basse fréquence (2 à 10 jours).

Il est évident que, dans les zones de fortes fluctuations thermiques, ces effets de la température pourraient être même plus importants, notamment aux basses fréquences du spectre des variations de pression.

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ACKNOWLEDGEMENTS

The experimental work for this report, organized by Rick Boyce and skillfully carried out by Jan Betlem, is gratefully acknowledged. I wish, also, to thank Brian Petrie for reading through the first draft and providing many useful suggestions and comments.

1. INTRODUCTION

It is well known (e.g., Wearn and Larson, 1982) that changes in temperature can affect the frequency response of quartz crystal transducers used in gauges for measuring pressure. Since one is interested in pressure as an oceanographic parameter, care must be taken to quantify resulting errors in pressure due to variations in temperature.

In this report, sensitivity to temperature is examined for eight Paroscientific pressure sensors as installed in gauges deployed during the winter and spring of 1984 on the Newfoundland Grand Banks.

Although temperature variations during the period were not large, that is to say, less than 5°C maximum difference with 0.7°C standard deviation for the most variable case, they could still significantly affect the relatively weak pressure variance at the low frequencies the experiment was designed to measure. For example, taking some typical values (to be discussed further in Section 4), the peak variance in these low frequency 'storm-driven' bands (2 to 10 day period) can be as low as 0.01 $dbar^2/cph$ for pressure and $1°C^2/cph$ for temperature. Taking a sensitivity value α = 0.01 dbar/°C (Section 3.1, also Wearn and Larson, 1980) leads to an error in the pressure variance density of approximatley 10% depending on the phase relation between the two signals. It will appear, from other examples from the spectra to be discussed in Subsection 4.1, that the errors due to temperature can be much higher, reaching up to 30% at low frequencies.

In view of the low energy levels involved, this report will include some discussion of the relative importance of temperature corrections and pressure resolution on the low frequency spectral bands, and

indicate what corrections, if any, might be applied to the 1984 Grand Banks bottom-pressure data.

Throughout, the sensitivity data will be compared with that of the more extensive experiments conducted by Wearn and Larson (1980, 1982).

2. CALIBRATION

In order to maintain the engineering (psi) units used for raw calibration data, supplied constants, corrections, etc., but to use oceanographic units (dbar and mbar) in referring to pressure gauges and presenting results, a mixture of units appears throughout the report. This causes little, if any, confusion. To convert, 1 psi = 0.68947 dbar.

2.1 Method

Each of the eight Aanderaa pressure gauges was placed horizontally in a Guildline constant temperature water bath, in pairs if two gauges of the same maximum range were available. They were held at temperatures of 0°, 5°, 10°, 15°, and 21°C for the duration of a calibration run, preceded by a stabilization period of 2 hr minimum. A calibration run consisted of a range of pressures, from atmospheric to full scale, applied to the gauge by means at a dead-weight tester. Data were recorded for both increasing and decreasing applied pressure, and barometric pressure was monitored and recorded continuously throughout each run. Further details of the calibration with examples of the calibration data are set out in Appendix 1.

Data recorded by the instruments represent the pressure-dependent vibration frequency of a Paroscientific quartz-crystal sensor. A recorded count number or frequency parameter, N, is defined by the relation

$$N = \int_{t=0}^{\tau} (f_c - f_p)\, dt \qquad (1)$$

where τ is an integration time, usually 40 seconds, f_c a constant frequency of 41 kHz, and f_p the variable pressure-dependent frequency ranging from about 40 kHz at zero pressure to about 36 kHz at full-scale pressure.

2.2 Regression Procedure

Following the procedure recommended in the WLR 5 reference manual (Aanderaa Instruments, 1982) and consistent with the predeployment calibration performed by the BIO Tidal Group, pressure is expressed by a third-order polynomial in N as

$$\hat{P} = \sum_{i=0}^{3} B_i N^i \qquad (2)$$

and the coefficients, B_i, are determined by multiple linear regression of applied pressure P_a with powers of N. For each gauge and for each of the five constant-temperature calibration runs, the regression was carried out twice: once for increasing and once for decreasing applied pressure. Tables of the resulting calibration coefficients are presented in Appendix 2.

It should be noted that, apart from a simple linear transformation of the coefficients, B_i, the calibration equation (2) is equivalent to that used by Wearn and Larson (1982) involving powers of inverse vibration period. Wearn and Larson, however, did not include a third-order term in their calibrations, since it was not justified by the accuracy of their pressure standard (dead-weight tester). The third-order term is included here mainly to be consistent with pre-deployment calibrations. Its

inclusion is not justified from the point of view of accuracy. The median rms residual error, $P_a - \hat{P}$, over all calibrations was 0.004 psi for the 280 dbar gauges and 0.04 psi for the 620 dbar gauges, whereas the accuracy of the applied pressure standards was ±0.03% of the reading for the 280 dbar gauges and ±0.06% of the reading for the 620 dbar gauges. Appendix 1 provides more detail of the accuracies, uncertainties, and corrections applied.

In calibrating the 620 dbar gauges, one or both of the 385 and 485 psi readings were usually unreliable due to operating the American Instruments (AMINCO) high-pressure balance below its minimum load. These points, along with occasional other outlying points, were rejected during the multiple regression procedure. The method was to examine the rms residual error after regression; if this was significantly (a factor of 3) greater than the median over all calibrations, the point of maximum residual was discarded and the regression recalculated. One, or at most two, extraneous calibration points were eliminated in this way from a number of the 620 dbar gauge calibrations. In fact, the above procedure reduced the overall maximum rms residual errors to 0.007 psi for the 280 dbar gauges and 0.06 psi for the 620 dbar gauges (Tables 5A-12A, Appendix 2).

2.3 Sensor Drift

During calibration of the 280 dbar gauge #47, applied pressure was also monitored with a precalibrated Paros 2400A pressure sensor. A sensor of this type is used in normal predeployment calibration of the gauges in preference to the more demanding task of estimating pressure from weights added plus various corrections. The purpose of including the monitor sensor here, however, was to monitor its drift in the 10 months since its

previous calibration in September 1983. The data (Tables 1A and 2A, Appendix 1) show a significant drift, reaching a maximum of about 0.08 psi (0.019% FSP) at 120 psi applied pressure. This is more than a factor of 10 greater than residual errors obtained (0.005 psi) in the regression analysis. These data show the importance, from the point of view of accuracy, of regularly recalibrating the monitor sensor.

Fortunately, pressure resolution, which is of greater importance than accuracy in field measurements, is little affected by these drift values or, indeed, by other similar systematic errors such as uncertainties associated with dead-weight testers. Further discussion of accuracy and resolution will appear in Sections 3.2 and 4.

3. TEMPERATURE SENSITIVITY

Wearn and Larson (1980) noted a decrease in sensitivity to temperature accompanying two design changes to the Paroscientific pressure sensor. The first occurred at sensor serial #350, when two internally pressurized bellows were replaced by a single internally pressurized bellows, and the second occurred at serial #1629, when the internally pressurized bellows was replaced by a single externally pressurized bellows. The more striking improvement came with the second design change, which appears to have reduced the sensitivity by almost a factor of 10. All the gauges to be examined here have sensors of the more recent design.

3.1 Estimates at Constant Sensor Frequency

For a fixed value of the crystal frequency-parameter, N, corresponding to a true applied pressure, P, at some temperature, $T_1 = T_0 + \Delta T$, say, a mean temperature sensitivity for the temperature interval $[T_0, T_1]$ can be

defined by the first difference relation

$$\alpha\ (N,\ T_0 + \Delta T/2) = \frac{\hat{P}_{T_0}(N(P,T_1)) - \hat{P}_{T_1}(N(P,T_1))}{\Delta T} \qquad (3)$$

where the subscripts T_0 and T_1 refer to the temperatures at which calibration coefficients were derived. In this sense, $\hat{P}_{T_0}(N(P,T_1))$ refers to the apparent pressure at $N(P,T_1)$ and $\hat{P}_{T_1}(N(P,T_1))$ refers to the true pressure, P, at $N(P,T_1)$. Using the above notation, a field pressure value at some temperature, T, say, is corrected to true pressure, P, by

$$P = \hat{P}_{T_0}(N(P,T)) - \alpha \cdot (T - T_0) \qquad (4)$$

provided T is in the interval $[T_0,\ T_1]$ for which α applies.

The reason for defining α as the RHS of (3), rather than its negative, is to ensure that $\alpha \to dP/dT$ as $\Delta T \to 0$ (see Appendix 4). Also, as it turns out, this definition is more consistent with that of Wearn and Larson (1982), giving a similar trend of α with temperature. Further discussion of the above and other methods of deriving α are presented in Appendix 4 and in Section 5.

Sensitivity values, α, were estimated according to (3) for each temperature interval for a range of N, chosen to span the pressure range for each gauge. The overall maximum and minimum values of α for each gauge are shown in Table 1. These values include estimates made from calibration runs both increasing and decreasing applied pressure. The map position numbers in Table 1 refer to the mooring positions shown in Figure 1, where the depth of each mooring is also indicated. Although some reference will be made to these mooring positions later in Subsection 4.1, its inclusion here is mainly for future reference.

Plots of sensitivity versus temperature for a variety of pressure

TABLE 1.

Range of temperature sensitivity values, over all pressures and temperatures, for each gauge. Map position numbers refer to positions marked in Figure 1.

Sensor Range (dbar)	Gauge Serial Number	Sensor Serial Number	Map Position Number	Range of Measured Temp. Sensitivity (mbar/°C)
280	372	-	1	0.4 to 2.1
	47	6672	2	-0.9 to 1.1
	344	15474	3	-0.4 to 0.3
620	65	15746	4	0.0 to 1.6
	350	15744	5	-0.8 to 1.2
	282	15317	6	-1.3 to 0.7
	109	15891	7	-1.9 to -0.3
	191	15894	10	-1.4 to 0.1

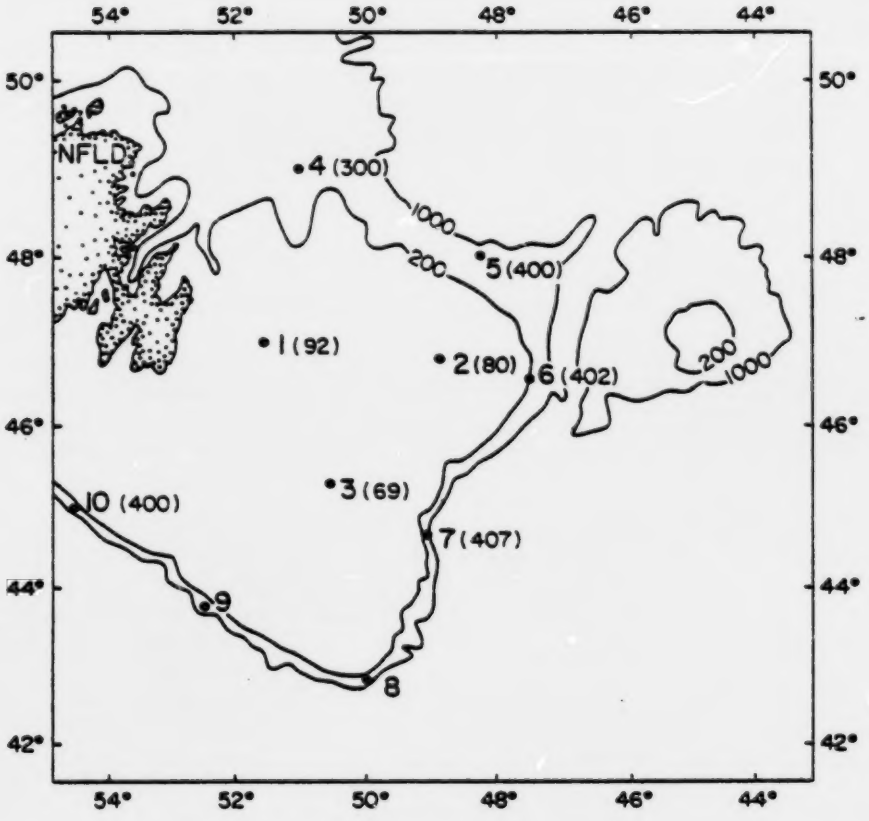

Figure 1. Reference map showing positions and depth (in brackets) of the bottom pressure gauges.

levels are shown, for each gauge, in Figures 2 to 9. For these, only calibrations for applied pressure increasing were considered. For further reference, all the sensitivity estimates are presented in Appendix 3.

From Table 1 and Figures 2 to 9, temperature sensitivity appears to depend quite strongly on both temperature and pressure and to vary from one gauge to another. The range of sensitivities is similar for both the 280 dbar and 620 dbar gauges with only one gauge, #344, showing extrema significantly under 1 mbar/°C. The extreme sensitivity over all gauges and calibrations is for gauge #372. Consulting Appendix 3, Table 13A, this value, 2.07 mbar/°C, occurs at 90 dbar in the 10° to 15°C temperature range derived from calibrations decreasing applied pressure. A similarly extreme value of -1.86 mbar/°C can be seen for gauge #109 at 570 dbar pressure, 0° to 5°C temperature range, and for increasing applied pressure.

The dependence of sensitivity on temperature and pressure varies between gauges. With the exception of gauge #350, Figures 2 to 9 show a tendency for all sensitivities to increase (in some cases becoming less negative) with increasing temperature. This increase is not linear, however. For gauge #47, for example, the rate of increase appears to be greater for higher temperatures, whereas for gauge #372 the opposite is true. With increasing pressure, the tendency for the 280 dbar gauges is to increase (in some cases becoming less negative) in sensitivity to temperature. For the 620 dbar gauges, on the other hand, sensitivity decreases with pressure (in some cases becoming more negative), for some gauges and at some temperatures quite sharply and approximately linearly. Examples are gauges #109 and #65 at tempeartures of 2.5°C and 12.5°C.

Comparing for increasing and decreasing applied pressures (Appendix 3), sensitivities usually agree within a few tenths of 1 mbar. This

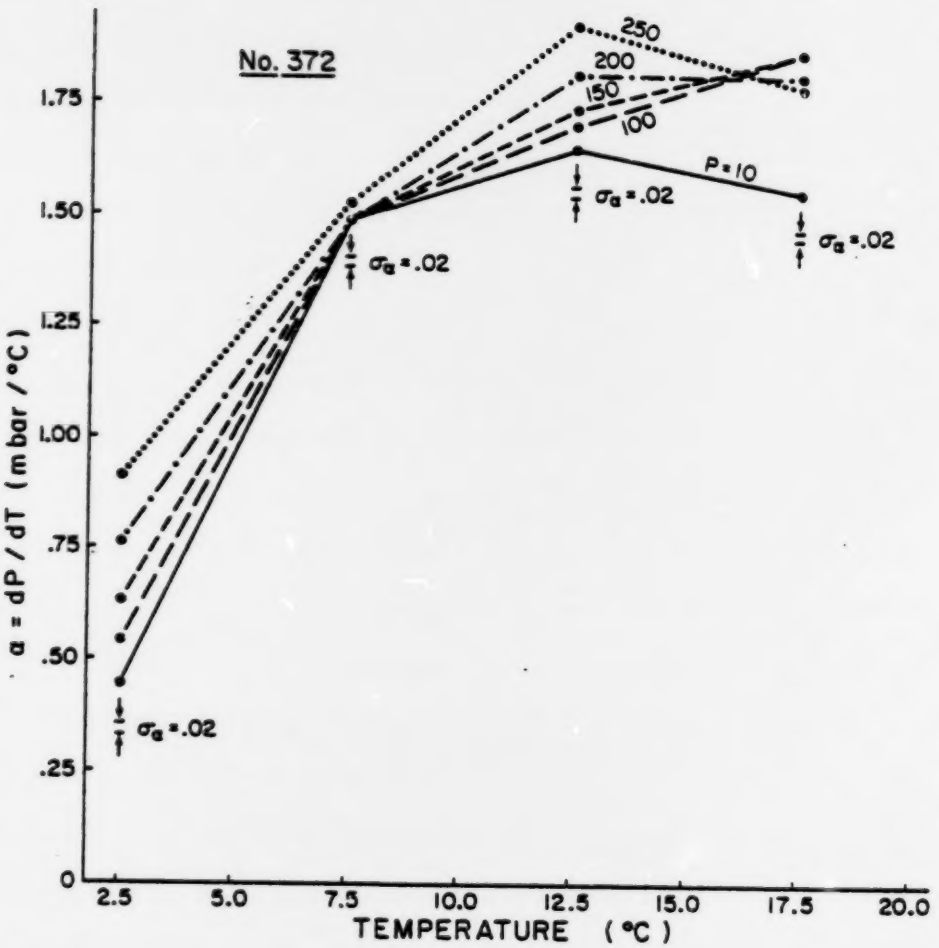

Figure 2. Temperature sensitivity plots at five applied pressures for gauge #372. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

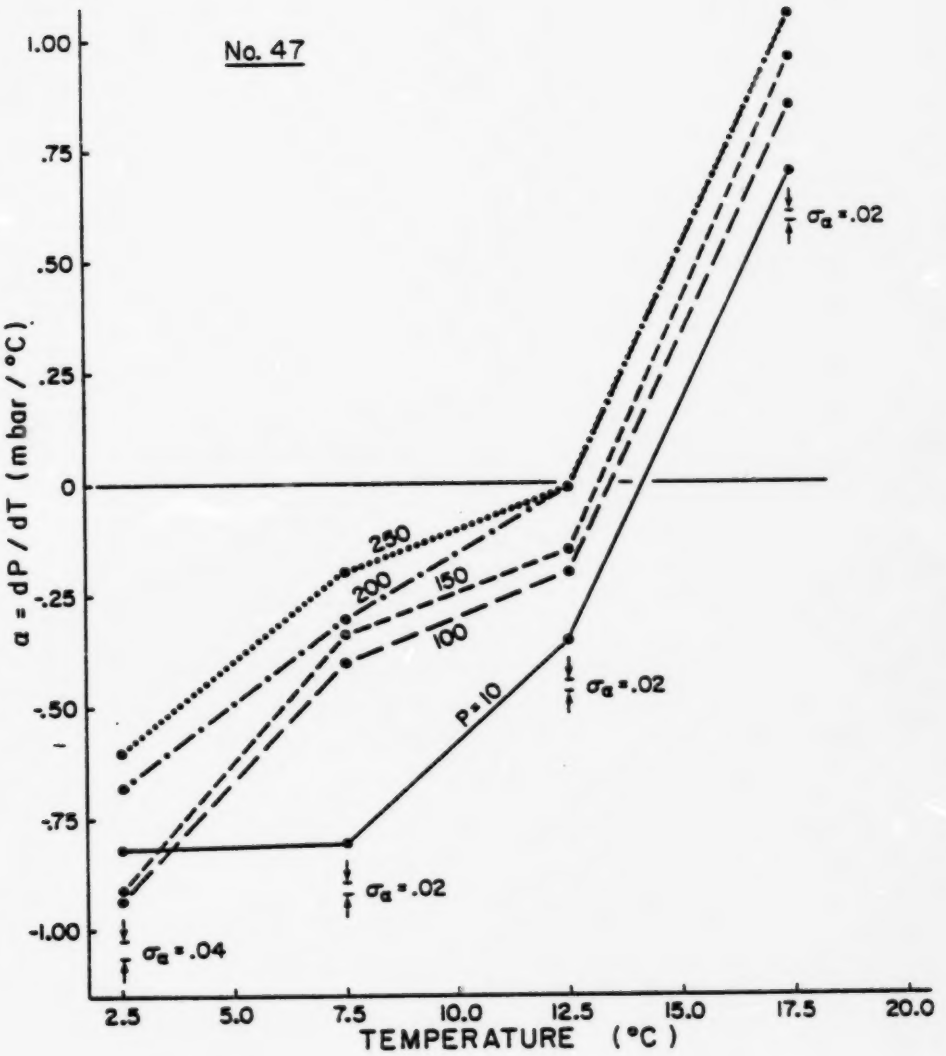

Figure 3. Temperature sensitivity plots at five applied pressures for gauge #47. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

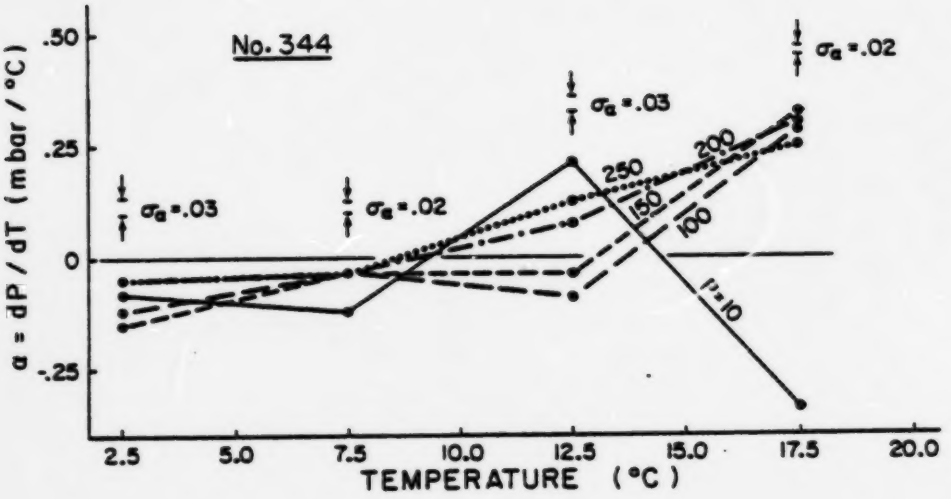

Figure 4. Temperature sensitivity plots at five applied pressures for gauge #344. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

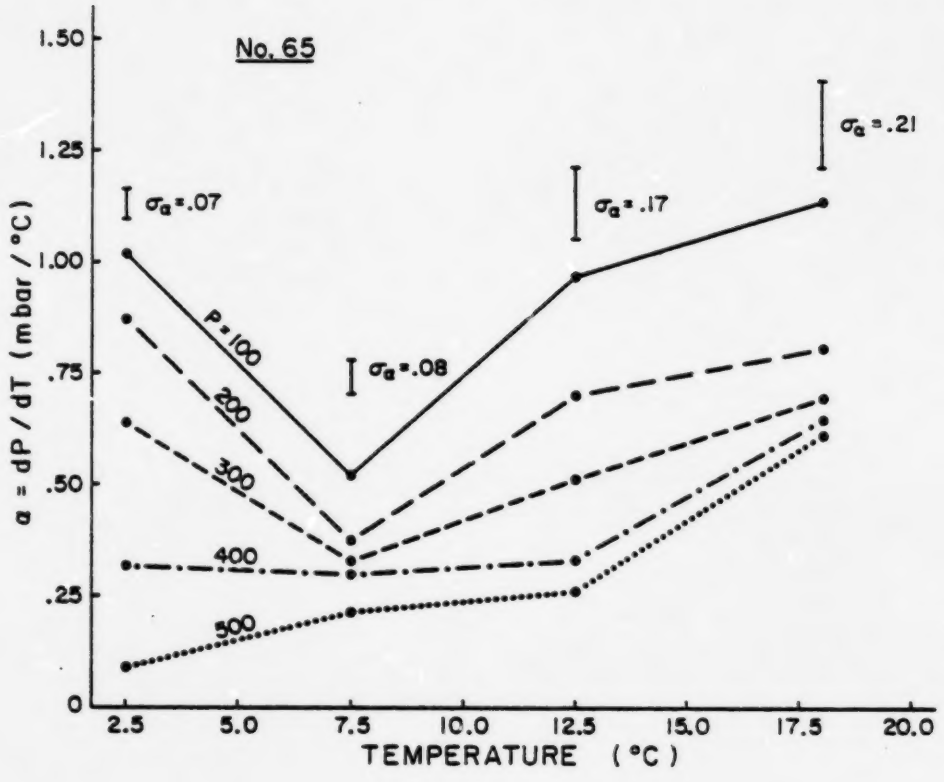

Figure 5. Temperature sensitivity plots at five applied pressures for gauge #65. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

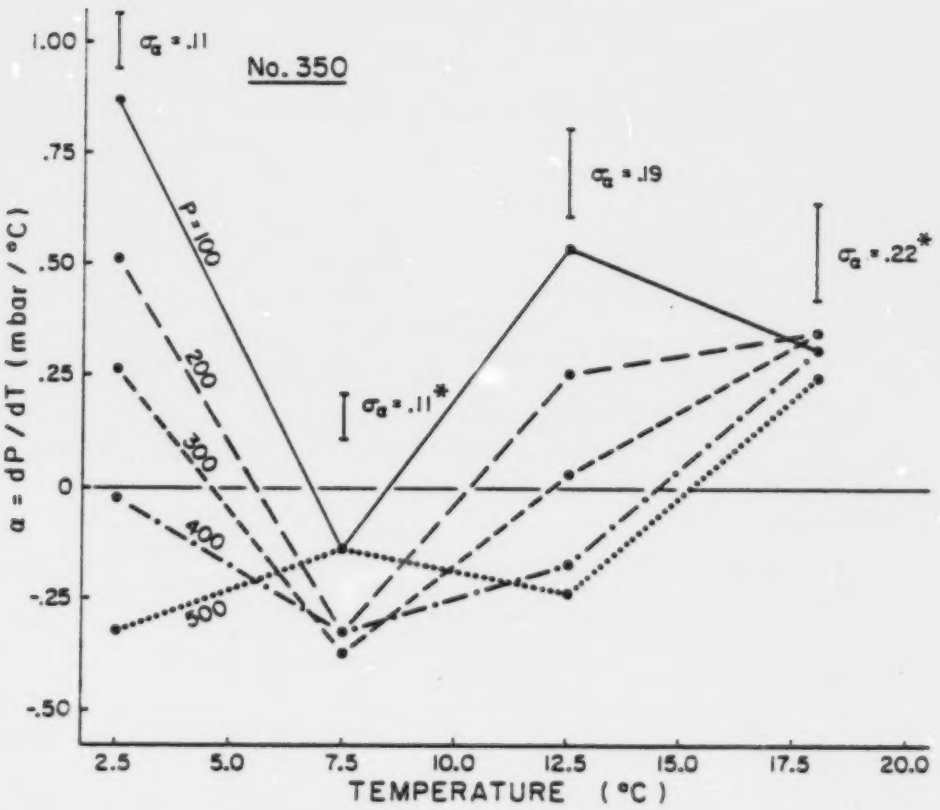

Figure 6. Temperature sensitivity plots at five applied pressures for gauge #350. The standard deviation in sensitivity for each temperature group is marked b a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

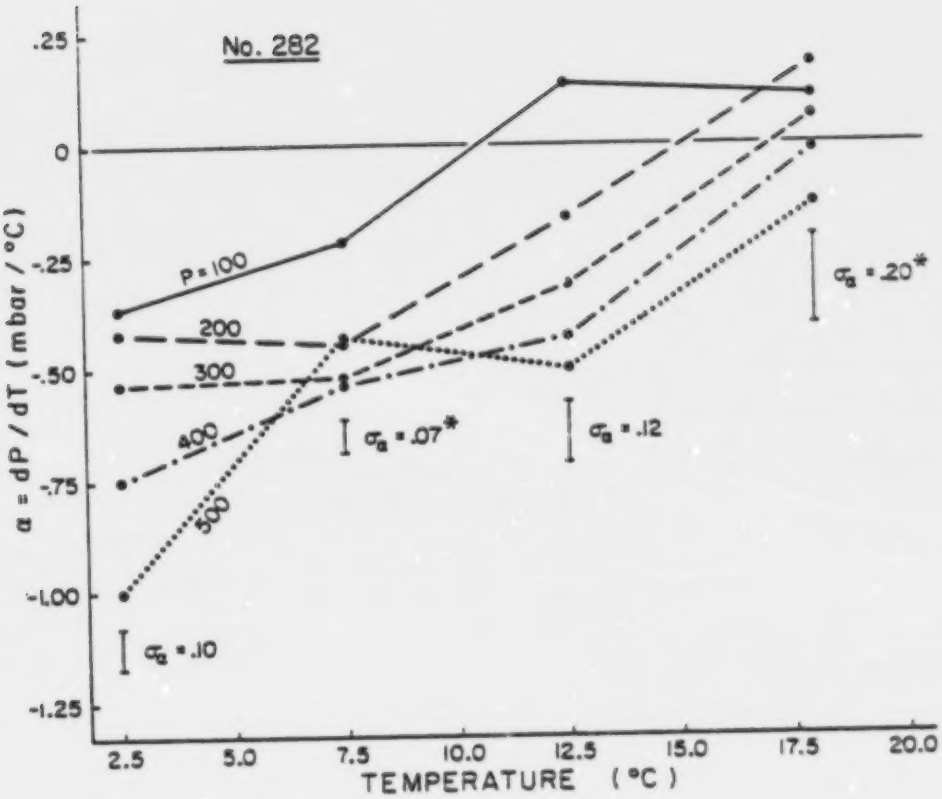

Figure 7. Temperature sensitivity plots at five applied pressures for gauge #282. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

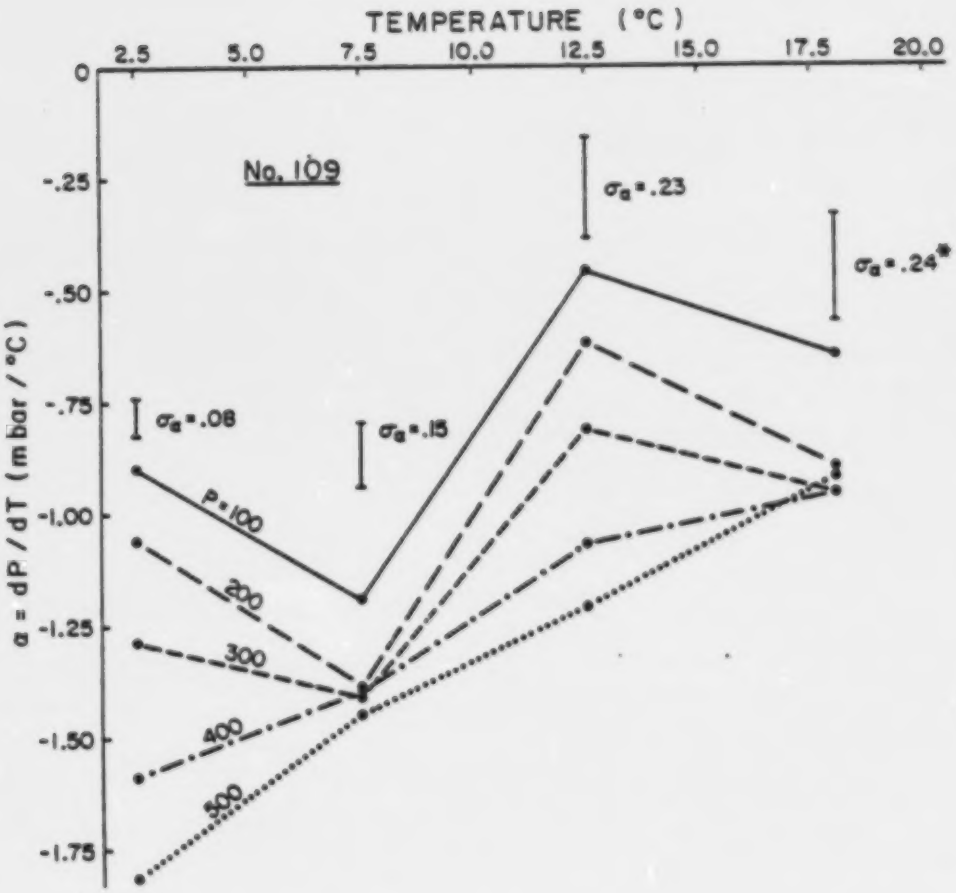

Figure 8. Temperature sensitivity plots at five applied pressures for gauge #109. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

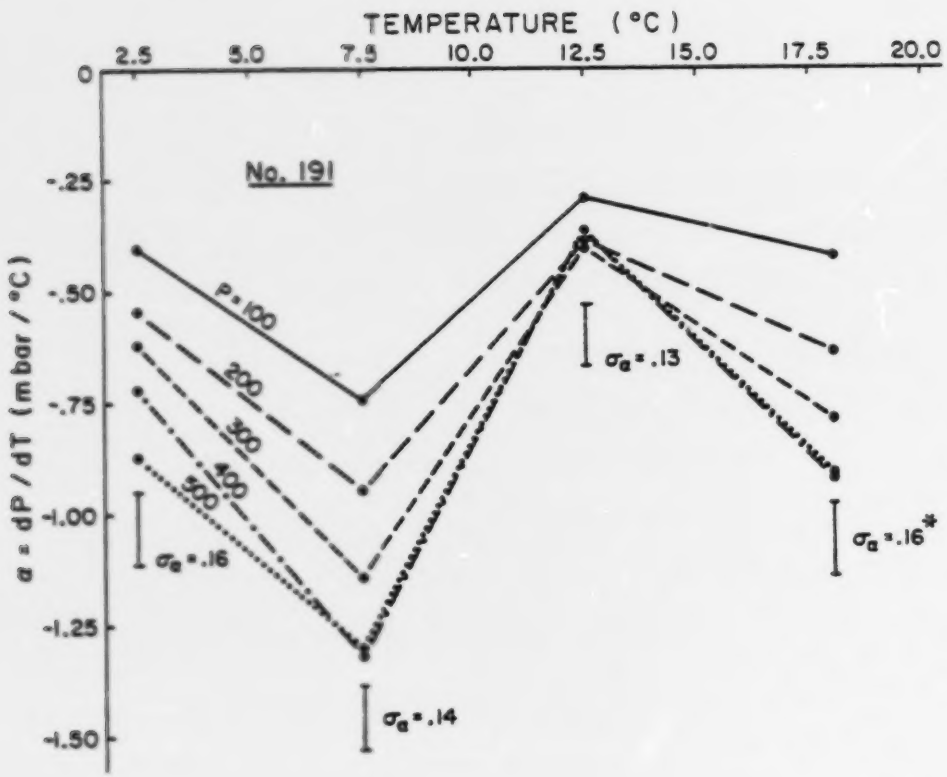

Figure 9. Temperature sensitivity plots at five applied pressures for gauge #191. The standard deviation in sensitivity for each temperature group is marked by a vertical bar and the asterisk, where present, indicates a degree of uncertainty in the plotted estimates (see text).

difference is due mainly to a hysteresis effect on the quartz crystal (Wearn and Larson, 1980). It is also due, in part, to the accuracy of calibrations.

Before discussing the accuracy of temperature sensitivity estimates, one further comparison is of interest. The range of sensitivities for the 620 dbar gauges is similar to that of Wearn and Larson (1980) for gauges of the same pressure range and Paros sensor type (i.e., with sensor serial numbers greater than 1629). Interestingly, comparison for the 280 dbar gauges also show similar temperature sensitivity ranges, despite the Paros sensors being of different design. Those of Wearn and Larson are all of the single internal bellows type, whereas those of the present study are all of the more recent external bellows type. It would appear, then, that the factor 10 decrease in sensitivities brought about by the design change, observed by Wearn and Larson for the 620 dbar gauges, has not occurred for the 280 dbar gauges.

3.2 Accuracy of Estimates

Before discussing the effects of temperature sensitivity on field measurements of pressure, some awareness of accuracy and standard deviations of the sensitivity estimates is necessary.

Temperature sensitivity accuracy depends, through the regression procedure, on accuracy of the gauge calibrations from which the sensitivity estimates were made. Many factors contribute to accuracy of calibration including: uncertainty errors associated with 'knowing' the applied pressure; systematic errors mostly caused by nonlinearity of the dead-weight tester, but also due to other conditions of the experiment; random noise associated both with the tester and with the gauge; and, finally, least

count (i.e., bit resolution) error in measurement of the sensor frequency parameter, N. Many of these contributions, some specified in Appendix 1, are of a similar order but it is not obvious how they combine. Most, but not all, will show up as residual errors in the regression procedure; others may appear as offset errors due to uncertainties in the 'zero' pressure, for example.

As was noted in Section 2, unlike accuracy, resolution of the pressure gauge (i.e., the precision with which small differences in pressure can be measured) will not be significantly affected by any of these calibration errors. It is fortunate, therefore, that resolution is of greater importance than accuracy in field measurements. This is simply because one is primarily interested in variability of pressure, which is sensitive to resolution, but not in its absolute value, which is sensitive to accuracy. Absolute pressure would only have a useful meaning if one also were to have a precise knowledge of the geopotential level of the instrument; a knowledge which, alas, is always lacking.

In estimating sensitivity to temperature, however, accuracy in calibration is extremely important. This is because the estimated sensitivity value is based on small differences in pressure derived, not from the same calibration, but from two separate calibrations - one at each temperature. A small difference in offset error between the two calibrations, for example, could lead to a large error in the sensitivity estimate.

It will be assumed in the following that offset errors will be predominantly in the same sense for the same gauge, calibrated at different temperatures. This is reasonable to the extent that experimental conditions will not change appreciably between neighbouring calibration runs. It will also be assumed that all the remaining errors are incorporated in

the regression residual errors so that, by analysis of these, an error bar can be established for the temperature sensitivity, α.

3.3 Standard Deviation of Estimates

In this section the variance of a temperature sensitivity estimate is examined in terms of the variance and covariance of the two constituent pressure estimates. Since these depend on the variance and covariance of the corersponding regression coefficients, Bi, in Equation 2, which, in turn, depend on the regression residual errors, an expression is derived relating the variance in estimated temperature sensitivity to the variance and covariance of the regression residual errors.

Using Equation 2, the variance of a predicted pressure value, $\hat{P}_0$, can be written in terms of some frequency-parameter value, N_0, as

$$V(\hat{P}_0) = V\left(\sum_{i=0}^{3} B_i N_0^{\,i}\right)$$

which expanded gives

$$V(\hat{P}_0) = V\left(\sum_{i=0}^{3} B_i N_0^{\,i}\right) + 2 \sum_{i=0}^{2} \sum_{j=i+1}^{3} \operatorname{cov}\left(B_i N_0^{\,i}, B_j N_0^{\,j}\right)$$

Assuming N_0 to be equal to its true value, $V(\hat{P}_0)$ becomes

$$V(\hat{P}_0) = \sum_{i=0}^{3} N_0^{2i}\, V(B_i) + 2 \sum_{i=0}^{2} \sum_{j=i+1}^{3} N_0^{\,i+j} \operatorname{cov}(B_i, B_j)$$

or in matrix notation

$$V(\hat{P}_0) = N_0^{T}\, C\, N_0 \qquad (5)$$

where $N_0^T = (1, N_0, N_0^2, N_0^3)$ and C is the variance-covariance matrix for the regression coefficients, B_i. Following Draper and Smith (1981, p. 83), C is written in terms of the normal equation matrix as

$$C = (N^T N)^{-1} V(\hat{e}) \tag{6}$$

where

$$N = \begin{pmatrix} 1 & N_1 & N_1^2 & N_1^3 \\ 1 & N_2 & N_2^2 & N_2^3 \\ \vdots & & & \\ 1 & N_n & N_n^2 & N_n^3 \end{pmatrix}$$

based on the n observed frequency-parameter values in the regression equation

$$P_a = NB + E \tag{7}$$

and $V(\hat{e})$ is the estimated variance of the regression residual errors, e_i. In (7) P_a is the vector of applied pressures, B the vector of regression coefficient, and E the residual error vector. Combining (5) and (6) gives

$$V(\hat{P}_0) = N_0^T (N^T N)^{-1} N_0 V(\hat{e}) \tag{8}$$

An assumption in the derivation of (6) is that the residual errors at each calibration point be distributed about their mean positions with the same variance and that they be pairwise uncorrelated (Draper and Smith, 1981, p. 24).

Assuming the temperature difference to be constant, the variance of a temperature sensitivity estimate is given by

$$V(\hat{\alpha}) = \frac{1}{\Delta T} V(\hat{P}_1 - \hat{P}_2)$$

$$= \frac{1}{\Delta T} [V(\hat{P}_1) + V(\hat{P}_2) - 2\ \mathrm{cov}(\hat{P}_1, \hat{P}_2)] \qquad (9)$$

where the subscripts 1 and 2 refer to calibration at temperatures T_1 and T_2, respectively. An expression similar to (8) can be derived for the covariance between $\hat{P}_1$ and $\hat{P}_2$ if one allows for covariance between residual errors at the two corresponding calibration points, but assumes all other pairs (for non-corresponding calibration points) to be uncorrelated. In the notation of (8) this is written as

$$\mathrm{cov}(\hat{P}_2, \hat{P}_2) = \mathbf{N}_0^T (\mathbf{N}_1^T \mathbf{N}_2)^{-1} \mathbf{N}_0\ \mathrm{cov}(\hat{e}_1, \hat{e}_2)$$

and (9) becomes

$$V(\hat{a}) = \frac{1}{\Delta T} [\mathbf{N}_0^T (\mathbf{N}_1^T \mathbf{N}_1)^{-1} \mathbf{N}_0\ V(\hat{e}_1) + \mathbf{N}_0^T (\mathbf{N}_2^T \mathbf{N}_2)^{-1} \mathbf{N}_0\ V(\hat{e}_2)$$

$$- 2\ \mathbf{N}_0^T (\mathbf{N}_1^T \mathbf{N}_2)^{-1} \mathbf{N}_0\ \mathrm{cov}(\hat{e}_1, \hat{e}_2)] \qquad (10)$$

Since corresponding calibration points were for approximately equal applied pressures, corresponding elements of the three matrices to be inverted differed by no more than 1 in 10^4 and the three matrix coefficients in (10) were virtually equivalent. The matrix terms, then, essentially constitute a single factor of proportionality relating the variance of $\hat{a}$ to the variance of the difference, $\hat{e}_1 - \hat{e}_2$, between corresponding regression residual errors.

Table 2 shows the variance contributions to the estimated standard deviation for the temperature sensitivity, as defined by (10), for each gauge at its approximate deployment depth and temperature range. We see that the standard deviations are much smaller than might be expected given the fairly high variance in estimated pressure values, particularly with

TABLE 2.

Based on the respective calibration equations at 0°C and 5°C, the table shows, for each gauge at its indicated deployment depth, estimates of the temperature sensitivity, α, with standard deviation given by $\hat{\sigma}_{\hat{\alpha}} = (V(\hat{P}_1) + V(\hat{P}_2) - 2\mathrm{cov}(\hat{P}_1,\hat{P}_2))^{1/2}$.

Gauge	Depth (m)	$\hat{\alpha}$ (mbar/°C)	$V(\hat{P}_1)$ $(\mathrm{mbar})^2$	$V(\hat{P}_2)$ $(\mathrm{mbar})^2$	$\mathrm{cov}(\hat{P}_1,\hat{P}_2)$ $(\mathrm{mbar})^2$	$\hat{\sigma}_{\hat{\alpha}}$ (mbar°C)
372	90.5	0.53	0.013	0.018	0.010	0.021
47	82.4	-0.94	0.022	0.031	0.013	0.033
344	66.9	-0.09	0.029	0.024	0.019	0.025
65	298.3	0.64	2.10	1.90	1.96	0.06
350	404.4	-0.02	2.15	2.55	2.19	0.11
282	405.4	-0.75	2.44	3.26	2.72	0.10
109	403.5	-1.59	3.28	2.98	3.06	0.08
191	403.8	-0.72	3.62	2.87	2.93	0.16

regard to the 620 dbar gauges. The reason is the high covariance between pressure estimates derived from calibration runs at different temperatures. This indicates the degree of repeatability in calibration errors when calibrating the same gauge at different temperatures.

Although the standard deviation for a pressure estimate is high, being of the same order or higher than a typical temperature sensitivity correction, it will apply, as in the case of bias errors, only to the absolute pressure and will not translate to the relative pressure. This is because the covariance between two neighbouring pressure estimates, pertaining to the same calibration equation, is almost exactly equal to the variance of each separate estimate.

Application of Equation 10 over the whole range of the sensitivity estimates presented in Appendix 3 has shown standard deviations to be consistently about twice as high near the extremes of the gauge pressure range as those near mid-range. Mid-range in this context refers to a fairly large span from about 100 to 500 dbar for the 620 dbar gauges and from about 40 to 240 dbar for the 280 dbar gauges. Since the standard deviations change only slightly over this mid-range, they have been depicted on the plots of Figures 2 to 9 as constant error bars of length 1 standard deviation, for each temperature interval.

Due to rejection of outliers in the regression procedure, some of the temperature sensitivity estimates were derived from calibration pairs with unmatched calibration points. This effect was investigated by rejecting a 'good' calibration point and observing the effect on sensitivity estimates. Since in some cases these did not lie within ±1 standard deviation of the good estimate, suspected sensitivity estimates in Figures 2 to 9 have been marked with an asterisk.

3.4 Sensitivity Estimates at Constant Pressure

Separate estimates of temperature sensitivity, α, were presented in Subsection 3.1 and Appendix 3, derived from calibrations both increasing and decreasing applied pressure. The difference between these was attributed, in part, to the hysteresis effect (Wearn and Larson, 1982). A third method, applied here only at instrument deployment pressures, was to obtain estimates of α by maintaining a nearly constant pressure and varying the temperature.

From Equation 4A derived in Appendix 4, α can be estimated by

$$\alpha = \frac{\partial \hat{P}}{\partial N} \frac{\Delta N}{\Delta T} - \frac{\Delta P}{\Delta T}$$

The term $\Delta P/\Delta T$ here represents a correction to apply allowing for small variations in the atmospheric contribution to the constant applied pres sure. The term $\partial \hat{P}/\partial N$, estimated from the appropriate calibration Equation 2, was found to be almost constant with temperature (although different for each gauge) so that the main variable determining α was the measured increment, ΔN, in the frequency parameter for a step change, ΔT, in temperature.

Values of α at gauge deployment depth, derived from the three separate estimates referred to above, are presented for each gauge and temperature interval in Table 3.

It was noted in Subsection 3.1 that estimates of α derived from calibrations first increasing and then deceasing the applied pressure generally agreed within a few tenths of 1 mbar/°C. This is borne out by the values of α_1 and α_2 in Table 3. Since the constant pressure estimates, denoted α_3 in Table 3, each represent an average over only two or four semi-independent samples, without regard to whether applied pressure had

TABLE 3

Comparison between temperature sensitivity values, α_1(mbar/°C), estimated: for i = 1 by holding constant the crystal vibration frequency, N, in formulae derived from calibrations at constant temperature and increasing applied pressure; for i = 2 as for i = 1 but decreasing applied pressure; and for i = 3 by holding applied pressure constant and varying temperature.

Gauge No.	Approx. Depl. Depth (m)	Temperature Range											
		0° - 5°C			5° - 10°C			10° - 15°C			15° - 21°C		
		α_1	α_2	α_3	α_1	α_2	α_3	α_1	α_2	α_3	α_1	α_2	α_3
362	90	0.53	1.02	0.69	1.49	1.35	1.44	1.69	2.07	0.79	1.86	1.59	-
47	82	-0.94	-0.81	-0.53	-0.45	-0.49	-0.50	-0.23	-0.22	-0.46	-0.81	0.91	-
344	67	-0.09	0.08	0.07	-0.06	-0.10	0.28	-0.05	0.14	0.32	0.14	0.13	-
65	405*	0.32	0.36	0.02	0.30	0.29	0.31	0.07	-0.13	0.66	0.55	-	-
350	404	-0.02	-	-	-0.32	-0.39	-0.14	-0.17	-0.43	0.0	0.32	-0.01	-0.25
282	404	-0.75	-	-	-0.53	-0.56	-0.46	-0.43	-0.85	-0.44	-0.01	-0.26	-0.37
109	404	-1.59	-1.51	-1.2	-1.40	-1.54	-1.40	-1.07	-1.22	-1.09	-0.94	-1.02	-
191	404	-0.72	-1.08	-0.85	-1.32	-0.84	-0.85	-0.36	-0.67	-0.74	-0.92	-0.75	-0.68

* Not the deployment depth.

just been increased or decreased, the reliability of the estimates is very low. An overall deviation of the α_3 estimate can be approximated by the formula

$$\hat{\sigma}_{\alpha_3} = \left(\frac{1}{\sum_{i=1}^{N} M_i} \sum_{i=1}^{N} \sum_{j=1}^{M_i} (\alpha_{3ij} - \bar{\alpha}_{3i})^2\right)^{1/2}$$

where $\bar{\alpha}_{3i}$ is the mean value of α_3 over the M_i (= 2 or 4) samples in the i^{th} class (i.e., gauge-temperature class) and N is the number of classes. Applying this formula over all gauges and temperatures, $\hat{\sigma}_{\alpha_3}$ was found to be 0.345 mbar/°C. All the estimates of α_3 shown in Table 3, with the exceptions of gauge #372 at 10° to 15°C and gauge #65 at 10° to 15°C, agree with at least one of the α_1 or α_2 values within the estimated deviation, $\hat{\sigma}_{\alpha_3}$.

4. CORRECTIONS TO FIELD MEASUREMENTS

What effect would temperature sensitivities of 1 mbar/°C have on pressure data from the 1984 Grand Banks pressure array? To examine this question we consider two worst cases. The maximum temperature sensitivity, α, is that of gauge #109 (position 7 in Figure 1), which is equal to -1.6 mbar/°C at deployment depth and temperature. Maximum low frequency (<1 cpd) temperature variability, on the other hand, occurs in the record from gauge #65 (position 4 in Figure 1), which has a slightly less extreme temperature sensitivity, α = 0.9 mbar/°C.

Sample spectra of pressure variance density and temperature variance density, together with coherence spectra and phase, are plotted for gauge #109 in Figures 10 and 11 and for gauge #65 in Figures 12 and 13.

4.1 Effect on Spectral Estimates

A simple formula for estimating temperature effect on pressure spectra, as a function of frequency, is easily shown to be

$$A_p = A_{\hat{p}} - 2\alpha(A_{\hat{p}}\, A_T)^{1/2}\, C_{\hat{PT}} \cos \theta_{\hat{PT}} + \alpha^2\, A_T \qquad (11)$$

where A_p, $A_{\hat{p}}$, and A_T are variance density spectra for temperature-corrected pressure, uncorrected pressure and temperature, respectively, and $C_{\hat{PT}}$ and $\theta_{\hat{PT}}$ are, respectively, the coherence and phase spectra between uncorrected pressure and temperature.

Due to nonlinearity, (11) is only valid as a correction formula when applied to raw spectral estimates before smoothing, in which case $C_{\hat{PT}} = 1$. More simply, if corrections are to be made, Equation 4 of Section 3 should be applied directly to the raw data. The use of (11), however, is more illuminating for discussion of errors, and in the examples to follow it provides a good estimate of corrections to apply since smoothing was limited to averaging over three adjacent frequency bands.

Equation 11 shows, as would be expected, that the temperature effect will be greatest when temperature and pressure are coherent, with a phase lag of either 0° or 180° and when the temperature variance is high. In Figure 11 we see that the coherence is high, particularly for the 105 hr and 60 hr bands and that the phase lag is close to 180° for all the low frequency bands. Taking the values $\alpha = -1.6$ mbar/°C given above for gauge #109, and the lowest frequency spectral estimate from Figures 10 and 11 of $A_{\hat{p}} = 0.046$ dbar^2/cph, $A_T = 11.8$°C^2/cph, $C_{\hat{PT}} = 0.63$, and $\theta_{\hat{PT}} = -156°$, Equation 11 gives a corrected spectral estimate of $A = 0.035$ dbar^2/cph. For this estimate, then, the pressure spectrum is over-estimated by 30.2%

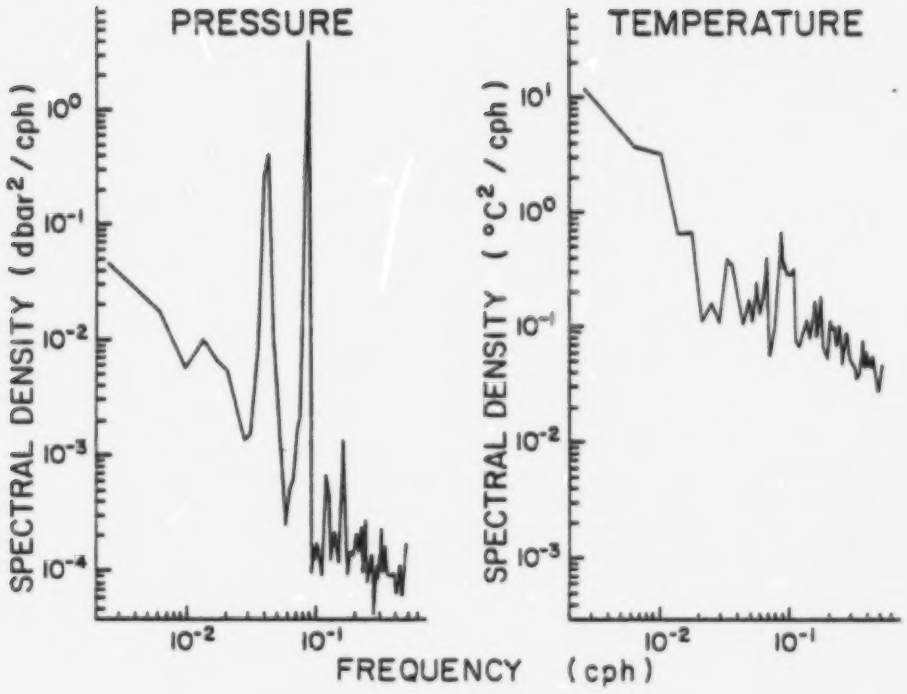

Figure 10. Sample pressure and temperature variance spectra for data recorded by gauge #109 at mooring site 7.

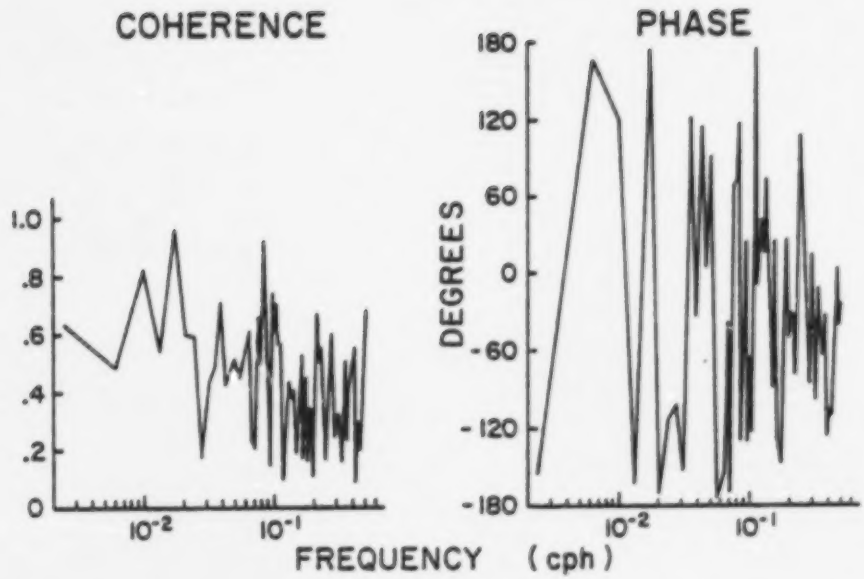

Figure 11. Sample coherence and phase spectra from data recorded by gauge #109 at mooring site 7.

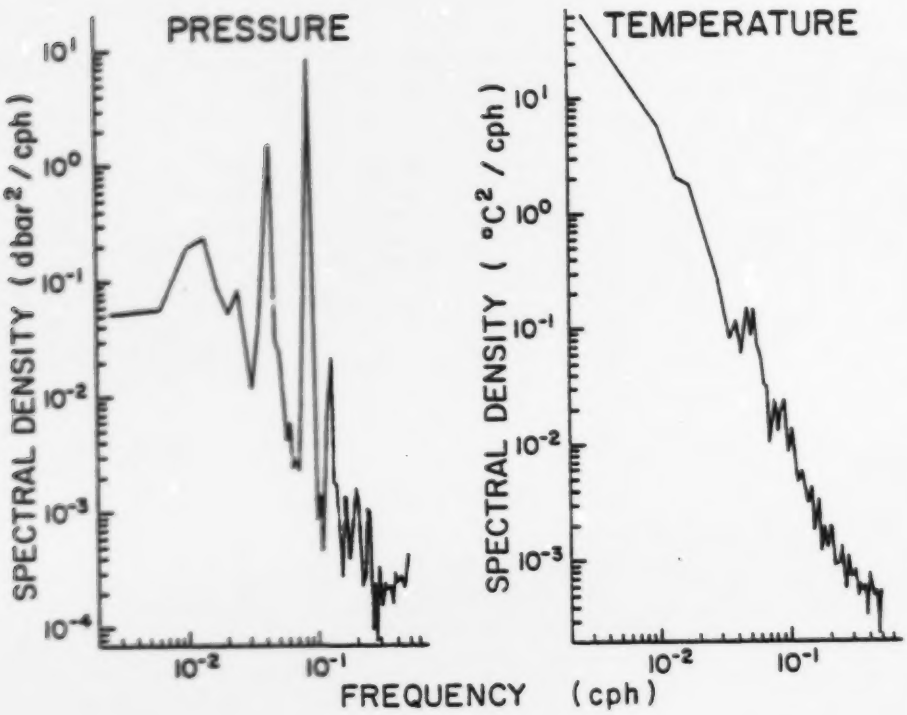

Figure 12. Sample pressure and temperature variance spectra from data recorded by gauge #65 at mooring site 4.

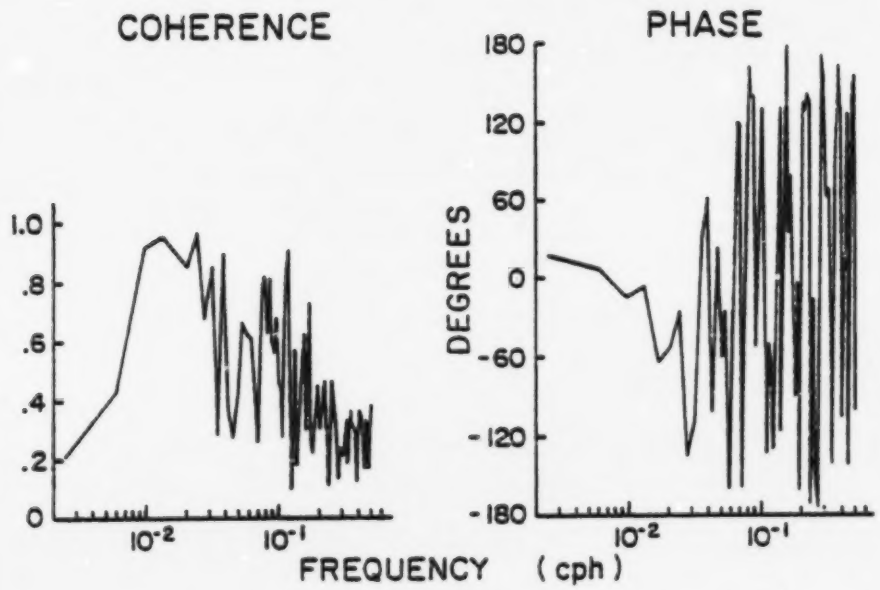

Figure 13. Sample coherence and phase spectra from data recorded by gauge #65 at mooring site 4.

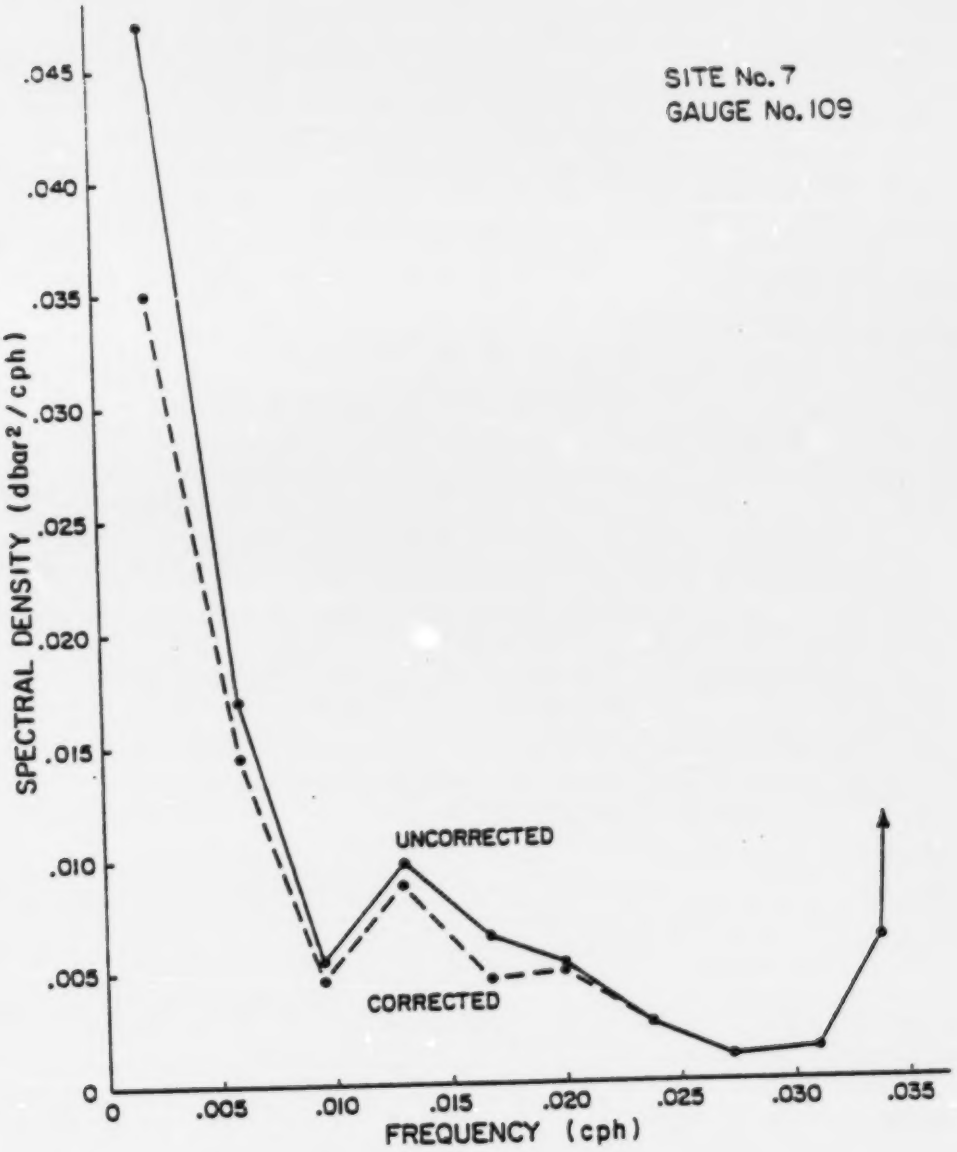

Figure 14. Linear plot showing the low frequency pressure spectrum before and after applying the temperature sensitivity correction for gauge #109.

due to the temperature effect. Similarly, estimates show that the next five spectral estimates are too high in energy by 19.5%, 19.4%, 13.2%, 39.8%, and 8.4%. These are plotted on linear axes in Figure 14.

The second example shows a very steep temperature variance spectrum (Fig. 12) and a pronounced low-frequency peak in the pressure variance spectrum. Comment on the shape of the temperature variance spectrum will appear later in Subsection 4.2. The coherence between presure and temperature (Fig. 13) is low for the first two bands but very high for the subsequent six bands. This time, the temperature and pressure are quite well in phase over this same low-frequency range and it is interesting to note that the temperature sensitivity value, $\alpha = 0.9$ (gauge #65), is positive. Apart from the possibility of the dynamics differing for the two separated mooring locations, the phase and temperature sensitivity reversals between the examples is suggestive of a strong temperature effect on pressure. Taking the values of $A_P^{\wedge}$, A_T, $C_{PT}^{\wedge}$, and $\theta_{PT}^{\wedge}$ from the spectra of Figures 12 and 13, application of Equation 11 shows that energy levels in the first six bands are too high by 3.4, 10.3, 9.0, 5.1, 3.2, and 3.7%, respectively. Although these percentage increases are lower than in the first example, the energy corrections are far larger due to the much higher energy level in the pressure spectrum. This is also generally true for the strong tidal peaks although the corrections are negligible in this case due to low temperature variance at these frequencies.

The effect of temperature errors on pressure appear not to alter the shape of the spectrum appreciably at low frequencies and so need not be applied for the purpose of identifying features in the spectrum. Should they need quantifying, however, or should coherence between pressure signals be of interest (not investigated here), it might be important to

correct for temperature.

4.2 Least-Count Resolution Effects on Spectra

The least count resolution (also called bit resolution) for the temperature sensor is approximately 0.035°C for the temperature range of gauge #65 measurements. This is also the sensor resolution level quoted in the operating manual (Aanderaa Instruments, 1982) and therefore the expected noise level of the instrument. If the least count error were at the noise level of the sensor, however, one would expect the temperature variance spectrum to flatten at a spectral density level of $A_N = 840\ a_N^2/2$ $°C^2$/cph, where 840 hr is the sample time series duration for Figure 12. Taking $a_N = 0.035/2$ gives $A_N = 0.13$ $°C^2$/cph, a value well above the high frequency energy levels of Figure 11.

A possible explanation for this is that the noise level, or sensor resolution level, is, in fact, well below the bit-resolution level and is thus not 'detected' by the spectrum. Instead, the spectrum shows the high-frequency contributions in the Fourier decomposition of a 'stepped' or 'layered' time series due to the least-count resolution. For lower frequencies the similar shape of the spectrum is due to the strong frontal structure evident in the time series (not shown here). Step changes of several °C were observed over a 4 hr period.

A similar least-count resolution for pressure also places a lower limit on energy which can be counted as signal. It is shown in Wearn and Larson (1980) that the Paros sensor resolution is at least one order of magnitude better than the value specified in the operating manuals (0.001% of full scale pressure). For the 620 dbar gauge #65 the least-count resolution at deployment depth is equal to about 0.004 dbar. This translates

to a spectral density level of $1.68 * 10^{-3}$ $dbar^2/cph$. Since the low frequency, low energy 'storm-band' peak in the pressure spectrum of Figure 10 is well above this level, the temperature corrections applied are well justified.

5. SUMMARY AND CONCLUSIONS

Eight Aanderaa pressure gauges, fitted with Paroscientific pressure transducers, were tested for temperature sensitivity. Three of the gauges tested were ranged at 280 dbar and five were ranged at 620 dbar.

Since application of pressure to the Paroscientific transducer decreases the oscillation frequency of its quartz crystal sensor, each gauge was calibrated by applying a range of pressures and then regressing applied pressure on a third-order polynomial in the measured frequency of the quartz crystal. The calibration was carried out for each gauge at five different temperatures.

Using the separate calibration equations and fixing frequency, a temperature sensitivity estimate was defined as the difference in pressure computed at two different temperatures divided by the temperature difference. Temperature sensitivities were thus computed for each gauge over the whole range of pressures and temperatures. Regarding these, the following conclusions can be drawn:

(1) The sensitivities over all gauges and over all calibrations ranged between -2 and +2 mbar/°C, consistent with results of Wearn and Larson (1980).

(2) The range of sensitivities was similar for both the 280 dbar and 620 dbar gauges.

(3) The sensitivities were strongly dependent on both temperature and pressure but varied in a different way for each gauge.

(4) Standard deviations for temperature sensitivity estimates were calculated to be within the range 0.01 to 0.05 mbar/°C for the 280 dbar gauges and 0.05 to 0.3 mbar/°C for the 620 dbar gauges.

(5) A hysteresis effect showed differences in temperature sensitivity, mostly within a few tenths of 1 mbar/°C, depending on whether estimates were derived from calibrations for increasing applied pressure or from calibrations for decreasing applied pressure.

(6) Separate estimates of sensitivity obtained by holding pressure nearly constant (at gauge deployment pressure) and varying temperature, though less accurate in this case, were found to be generally within one deviation (as estimated in Subsection 3.4) of at least one of the two other estimates referred to in (5) above.

(7) An earlier change in design of Paros sensors from a single internal bellows to a single external bellows did not appear to decrease the temperature sensitivity for the 280 dbar gauges as was noted by Wearn and Larson (1980) for the 620 dbar gauges.

Field data, collected from deployment of these same gauges on the Newfoundland Grand Banks during winter and spring of 1984, were examined for temperature effects on measured pressure. The method was to compute the corrections applicable to the variance in each frequency band of the pressure spectrum. Following are the conclusions:

(8) For five of the gauges (#47, 344, 372, 282, and 350) the temperature effect on pressure was not significant, reaching typically about 1% of the pressure variance at low frequencies and less for higher frequencies.

(9) The temperature effect was significant, however, for three of the more sensitive gauges (#65, 109, and 191) deployed in areas of relatively higher temperature variability. Errors were highest, in percentage terms, in the lower frequency bands where temperature variance was highest and pressure variance low. Applicable corrections for bands below 0.5 cpd ranged between 3% and 40%.

(10) Although temperature sensitivity corrections to pressure might not be necessary for the 1984 Grand Banks data, with the three possible exceptions referred to above, corrections will be necessary when interest is focussed on low frequency pressure variance in areas of high temperature variability.

(11) The present report has provided one realization of temperature sensitivity values for eight pressure gauges. The stability of these estimates is still not known. It is suggested, therefore, that for measurements where temperature effects are likely to matter, based, for example, on a nominal value of $\alpha = 1.5$ mbar/°C, that temperature sensitivities for these gauges be recalculated; at least for appropriate deployment depths and temperatures.

Since in practice the pressure gauges are measuring over a range of only a few metres, with temperature varying over typically less than 10°C, an alternative method to determine temperature sensitivity, involving small changes in applied pressure and temperature, might be more appropriate than the other methods of this report.

Taking derivatives of the frequency parameter, $N(P,T)$, with respect to temperature and pressure to be constant over the small range of interest, a Taylor expansion written in the form

$$\varepsilon_i^2 = \{\Delta N_i - (\frac{\partial N}{\partial P}\Delta P_i + \frac{\partial^2 N}{\partial P^2}\frac{\Delta P_i^2}{2}$$

$$+ \frac{\partial N}{\partial T}\Delta T_i + \frac{\partial^2 N}{\partial T^2}\frac{\Delta T_i^2}{2} + \frac{\partial^2 N}{\partial P \partial T}\Delta P_i \Delta T_i)\}^2 \qquad (12)$$

could be applied to each calibration increment (ΔP_i, ΔT_i, ΔN_i), where ε_i is some unknown residual error. Minimizing $\sum \varepsilon_i^2$ over a set of increment values, with respect to the unknown derivatives, would yield least squares estimates of these derivatives with a variance propotional to the rms residual error. Temperature sensitivity would then be given by

$$\alpha = \frac{dP}{dT} = \frac{\partial P}{\partial N}\frac{dN}{dT} = \frac{\partial N}{\partial T}\frac{\partial N}{\partial P} \qquad (13)$$

Providing a sufficiently large number of calibration points were obtained (e.g., more than 10), accurate estimates of not only α, but also of $\partial\alpha/\partial P$ and $\partial\alpha/\partial T$, could be derived for the relevant depth and temperature. This method is suggested for future temperature sensitivity studies.

6. REFERENCES

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APPENDIX 1

EXPERIMENTAL DETAILS

1.1A BASIC PROCEDURE

The gauges were placed horizontally in the Guildline constant temperature water bath, in pairs, when two gauges of the same maximum range were available. They were held at temperatures of 0°, 5°, 10°, 15°, and 21°C for the duration of a calibration run preceded by a minimum stabilization period of 2 hr. A calibration run consisted of a range of pressures applied from barometric to full-scale pressure, from a number of dead-weight testers. During heating phases from 0° to 5°C, 5° to 10°C, etc., the gauges were held at a constant pressure approximately representing deployment depth (400 m for 620 dbar gauges and 75 m for 280 dbar gauges). Following a fast temperature rise of 5°C in less than 15 min, data were recorded every 5 min for about 30 min or more while the bath temperature stabilized. The gauges were then left to stabilize for several hours, or overnight, before calibration at the new temperature was begun. Barometric pressure was monitored and recorded continuously during all calibrations.

1.2A STANDARDS

(a) Barometer

- Type: Paros. Mod. 230-A-002, pressure transducer S/N 1507
- Read in psi via a Paros. Mod. 600 pressure computer, range 0-30 psi
- A correction of +0.018 psi applied
- Data for programming of MOD 600 derived from N.R.C. OAL Report No. MOP 306, December 1982

(b) Pressure Balance (280 dbar gauges)

This is a gas system (instrument grade dry nitrogen) dead-weight tester used for the 280 dbar gauges S/N 47, 344 and 372.

- Type: pneumatic pressure balance, AMETEK M&G Model HK500, S/N 72068, range up to 500 psi.
- Minimum load equal to weight of carrier, 200 g, producing 10 psi.
- Calibration at N.R.C., November 1982, Report #MOP 303 gives uncertainties of ±0.02% in effective piston area and ±0.001% (@ 20°C) of mass for each 2 kg weight (1 kg produces 50 psi). These confirm manufacturer's specification and certificate of compliance dated February 1980.
- Accuracy of generated pressure at 50% greater than minimum load is ±0.025% of reading or ±0.025 psi, whichever is the greater.
- Observed repeatability and noise level <0.01% of reading.
- Applicable correction + 0.0014% F/A, F = force of weights, A = piston area.
- The total or absolute pressure applied to the gauges was therefore calculated as

$$P_A = (1 + 0.0014\%)\ F/A + P_B + 0.018 \text{ psi}$$

with P_B the uncorrected barometric pressure.

(c) Pressure Balances (620 dbar gauges)

Two oil system pressure balances (dead-weight testers) were required for calibration of the 620 dbar gauges (S/N 65, 350, 109, and 191): one for the range 0 to 400 psi, marked 'B' on the calibration sheets, the other for the range 400 to 900 psi, marked 'A' on the calibration sheets. As discussed below, problems with piston binding occurred when changing between 'B' and 'A' balances.

(1) Low pressure balance

- Type: Barnett MOD 5250/1 #2706/70.
- Mass of one sample weight determined at Department of Consumer Affairs, Burnside Industrial Park, September 1978.
- Effective piston area certificate dated December 1970.
- Calibration last verified within ±0.01% of reading from 29 to 375 psi using a Paros 2400A sensor S/N 2121 (N.R.C. Report MOP 10312 November 1978).
- Accuracy of generated pressure at output ports (per instrument specification) ±0.03% of reading.
- Minimum load 21 psi (one weight producing 21 psi plus carrier and piston).
- Repeatability proven less than ±0.01% of reading from minimum load up.
- Nominal applied pressure equals force of weights (F) divided by effective piston area (A).
- Applicable corrections are +0.008% F/A + TARE.
  TARE pressure accounts for weight of oil column between output port and relative height of test gauge location. Since the gauges in the water bath were about 16 inches below this reference level, and the type of oil used in the system generated a pressure of approximately 0.032 psi per inch of vertical displacement, TARE pressure was calculated for each pair of gauges, as installed in the bath, and recorded on the calibration sheets.

- The total or absolute pressure applied to the gauges was therefore calculated as

$$P_A = (1 + 0.008\%)\ F/A + TARE + P_B$$

with P_B the barometric pressure.

(ii) <u>High Pressure Balance</u>

- American Instruments (AMINCO) Type 47-12221 S/N B8820; range up to 20 000 psi.
- Minimum load 6.25 kg ≡ 500 psi generated by piston assembly, yoke, and weight pan without additional weights.
- Stated accuracy for pressures above minimum load: ±0.01% of reading or ±2 psi, whichever is greater; applicable when other corrections such as for gravity, temperature, compression, etc., have been made. For practical purposes, a combined correcton factor of:

  F/A - 0.13% below minimum load

  F/A - 0.12% above minimum load

  is currently in use.
- Overall uncertainty of generated true pressure is ±0.06% of reading due to uncertainty of N.R.C. calibration report No. MOP 103/1, November 1978, 'Calibration of Piston-Cylinder Assembly MOP 47-12221 #38820 @ 20°C.' Apparently this calibration was performed with a piston load of 1.25 kg force, which is 20% of stated minimum load, creating problems with piston binding.

- The mass of each of the 25 kg (2000 psi), 12.5 kg, 6.25 kg, and 2.5 kg weights was determined at Weights and Measures, Burnside, September 1978. The F/A - 0.13% and F/A - 0.12% corrections were calculated from these data.
- This balance had to operate below minimum load at pressure points of 385 and 485 psi. This was achieved by lifting the yoke and weight pan and loading small weights directly on the piston, provided the latter was sufficiently free and truly floating in its oil. The technique was to run the balance at some high pressure above 400 psi for several minutes before attempting any low load condition. Despite this precaution, piston binding problems were still encountered causing errors in the calibration points. These problems disappeared at pressures of 585 psi and up.
- The absolute pressure was calculated for each calibration point as

$$P_A = (1 - 0.13\%)\ F/A + TARE + P_B$$

with P_B the barometric pressure.

(iii) Linearity

- The linearity of all balances, oil or gas operated, is primarily a function of the uniformity and the uncertainty of mass determination for each weight, provided the instrument is operated above minimum load level. This factor is less than ±0.005% of reading for the three systems in use. Piston and cylinder deformation under high pressure, another factor affecting linearity, had no effect

in this case. The gas balance showed some nonlinearity due to pressure regulation action, which at present is not determined. Intercomparison via a Paros 2400A quartz transducer (described below) showed the same deviation when calibrated against the Barnett 5250/1 oil system as when calibrated against the AMETEK HK500 gas system, within ±0.015% of reading.

(d) Monitor Gauge

Data from this gauge were only recorded for comparison with estimated applied pressures. They were not used in calibration of the gauges.

Since gauges do not provide 'intelligible' output, it is standard practice to monitor the applied pressure with a Paros Mod. 2400-A quartz transducer and readout system (Mod. 600 pressure computer) which can accommodate simultaneously the Paros 230-A-002 used as a barometer and the 2400-A monitor, programmed independently for each transducer. Constants for the 2400-A were derived from its last calibration versus the HK500 in September 1983. The readings of the 2400-A are also listed on the calibration sheets, together with differences, ΔP, between the 2400A and the standard, expressed as a percentage of full-scale pressure (400 psi for the 2400-A). These differences are due to crystal drift since the previous calibration.

1.3A EXAMPLES OF CALIBRATION DATA

Examples of the calibration data are shown in Tables 1A to 4A. In these, the contributions to the true (absolute) applied pressure, P_A (in units psi), are indicated and, for gauge #47, the Paros 2400A monitor

reading is also shown. The frequency parameter N is estimated as

$$N = 1024 \cdot (CH\#3) + (CH\#4)$$

Channel #2 is a temperature count not connected for gauge #47.

Absolute pressures marked with an '*' symbol were those calibration points rejected in the calibration analysis.

TABLE 1A

Calibration data for gauge #47 @ 0°C with units in psi.
HK500 correction + 0.0014% F/A, Barometric correction + 0.018 psi.

Applied Pressure HK500				Paros 2400 A		Gauge # 47		
Nominal F/A	Corrected	Barometric	Absolute P_A	P_1	ΔP % FSP	Ch#2	Ch#3	Ch#4
0	0	14.5654	14.5834	14.5791	-0.001	1	399	105
15	15.0020	14.5660	29.5860	29.6121	0.007	1	413	277
45	45.0061	14.5651	59.5892	59.6395	0.012	1	442	89
75	75.0101	14.5640	89.5921	89.6485	0.014	1	471	635
105	105.0142	14.5609	119.593	119.658	0.016	1	501	925
135	135.0183	14.5636	149.600	149.662	0.016	1	532	1006
165	164.0223	14.5645	179.605	179.662	0.014	1	564	904
195	195.0264	14.5656	209.610	209.660	0.013	1	597	665
225	225.0304	14.5684	239.617	239.665	0.012	1	631	338
255	255.0345	14.5698	269.622	269.663	0.010	1	665	974
285	285.0385	14.5693	299.626	299.663	0.009	1	701	580
315	315.0425	14.5722	329.633	329.675	0.011	2	738	239
345	345.0466	14.5715	359.636	359.684	0.012	2	775	1017
375	375.0506	14.5714	389.640	389.695	0.014	2	814	923
315	315.0425	14.5698	329.630	329.675	0.011	2	738	219
255	255.0345	14.5700	269.623	269.670	0.012	2	665	955
195	195.0264	14.5702	209.615	209.677	0.016	2	597	646
135	135.0183	14.5704	149.607	149.687	0.020	2	532	1000
75	75.0101	14.5710	89.5991	89.6786	0.020	2	471	636
15	15.0020	14.5714	29.5914	29.6435	0.013	2	413	295
0	0	14.5722	14.5905	14.6090	0.005	2	399	122
0	0	14.5722	*	14.6055	0.004	2	399	127
105	105.0142	14.5715	*19.604	119.682	0.020	2	501	926

* Data not included in calibration.

TABLE 2A

Calibration data for gauge #47 @ 5°C with units in psi.
HK500 correction + 0.0014% F/A, Barometric correction + 0.018 psi.

Applied Pressure HK500				Paros 2400 A		Gauge # 47		
Nominal F/A	Corrected	Barometric	Absolute P_A	P_1	ΔP % FSP	Ch#2	Ch#3	Ch#4
105	105.0142	14.5750	*119.6073	119.679	0.108	3	501	900
0	0	14.5729	* 14.5912	14.6055	6.004	3	399	99
0	0	14.5668	14.5851	14.5879	0.001	3	399	59
15	15.0020	14.5659	29.5859	29.6200	0.009	3	413	208
45	45.0061	14.5659	59.5900	59.6479	0.015	3	442	23
75	75.0101	14.5653	89.5934	89.6569	0.016	3	471	563
105	105.0142	14.5653	119.5975	119.672	0.019	3	501	863
135	135.0183	14.5663	149.603	149.671	0.017	3	532	939
165	165.0223	14.5668	179.607	179.667	0.105	3	564	842
195	195.0264	14.5667	209.611	209.665	0.014	3	597	604
225	225.0304	14.5671	239.616	239.668	0.013	3	631	268
255	255.0345	14.5675	269.620	269.668	0.012	3	665	915
285	285.0385	14.5676	299.624	299.668	0.011	3	701	517
315	315.0425	14.5684	329.629	329.675	0.012	3	738	172
345	345.0466	14.5688	359.633	359.685	0.013	3	775	959
375	375.0506	14.5687	389.631	389.695	0.014	3	814	861
315	315.0425	14.5698	329.630	329.680	0.012	3	738	171
255	255.0345	14.5699	269.622	269.676	0.013	3	665	900
195	195.0264	14.5698	209.614	209.678	0.016	3	597	597
135	135.0183	14.5698	149.606	149.687	0.020	3	532	944
75	75.0101	14.5710	89.5991	89.6752	0.019	3	471	569
15	15.0020	14.5715	29.5915	29.6435	0.013	3	413	235
0	0	14.5706	14.5889	14.6081	0.005	3	399	71
0	0	14.5722	* 14.5905	14.6020	0.003	3	399	64
105	105.0142	14.5722	*119.604	119.689	0.021	4	501	877

* Data not included in calibration.

TABLE 3A

Calibration data for gauges #65 and #109 @ 0°C with units in psi.
A = AMINCO #B8820, correction -0.13% F/A + TARE, TARE = 0.325 psi
B = BARNETT #1706/70, correction - 0.008% F/A + TARE

	Applied Pressure			Gauge # 65			Gauge # 109		
	Nominal F/A	Barometric	Corrected Absolute P_A	Ch#2	Ch#3	Ch#4	Ch#2	Ch#3	Ch#4
	0	14.6600	15.0120	79	81	858	75	21	134
B	85	14.6587	100.0175	80	96	337	75	35	488
	185	14.6584	200.0252	79	113	563	75	52	695
	285	14.6579	300.0327	79	130	1003	75	69	683
B	385	14.6580	400.041	80	148	643	75	87	37
A	385	14.6580	399.51	79	148	562	75	86	982
	485	14.6575	499.379	80	166	426	75	104	517
	585	14.6581	599.150	79	184	560	75	122	283
	685	14.6581	699.120	80	202	941	76	140	253
	785	14.6568	789.988	80	221	557	76	158	439
	885	14.6566	898.858	79	240	466	75	176	874
	785	14.6563	798.988	80	221	554	75	158	433
	685	14.6567	699.118	80	202	932	75	140	242
	585	14.6566	599.248	79	184	558	75	122	278
	485	14.6560	499.377	79	166	427	75	104	516
A	385	14.6549	*399.507	79	148	431	75	86	848
B	385	14.6535	400.0363	80	1458	637	75	87	27
	285	14.6536	300.0284	79	130	1001	75	69	676
	185	14.65378	200.0205	80	113	565	75	52	490
B	85	14.6530	100.0118	79	96	339	75	35	486
	0	14.6525	15.0045	79	81	864	75	21	136
	0	14.6532	* 15.0052	80	81	859	75	21	134
A	585	14.6558	*599.247	79	184	558	75	122	280

* Data not included in calibration.

TABLE 4A

Calibration data for gauges #65 and #109 @ 5°C with units in psi.
A and B corrections as in Table 3A.

	Applied Pressure			Gauge # 65			Gauge # 109		
	Nominal F/A	Barometric	Corrected Absolute P_A	Ch#2	Ch#3	Ch#4	Ch#2	Ch#3	Ch#4
A	585	14.6527	*599.244	223	184	556	219	122	273
	585	14.6500	*599.242	224	184	554	220	122	268
	0	14.6485	* 25.0005	24	81	869	219	21	129
	0	14.6415	14.9935	225	81	866	220	21	120
B	85	14.6409	99.9997	226	96	347	221	35	474
	185	14.6402	200.0070	225	113	572	221	52	479
	285	14.6403	300.015	226	130	1009	221	69	665
B	385	14.6408	400.024	225	148	649	221	87	18
A	385	14.6426	399.494	226	148	569	221	86	965
	485	14.6427	499.364	225	166	432	220	104	498
	585	14.6428	599.234	226	184	560	221	122	260
	685	14.6426	699.104	225	202	936	221	140	222
	785	14.6420	798.974	225	221	558	221	158	413
	885	14.6418	898.843	226	240	464	221	176	847
	785	14.6417	798.973	226	221	556	221	158	411
	685	14.6416	699.103	225	202	935	222	140	220
	585	14.6415	599.233	225	184	556	221	122	252
	485	14.6412	499.363	225	166	426	221	104	490
A	385	14.6403	399.492	226	148	570	221	86	961
B	385	14.6394	*400.022	226	148	643	221	87	8
	285	14.6392	300.014	225	130	1007	222	69	659
	185	14.6390	200.0058	225	1134	572	221	52	473
B	85	14.6390	99.9978	225	96	349	221	35	472
	0	14.6385	14.9905	225	81	873	221	21	122
	0	14.6387	* 14.9907	225	81	870	221	21	121
	585	14.6382	*599.228	225	184	558	221	122	256

* Data not included in calibration.

APPENDIX 2

CALIBRATION COEFFICIENTS

Tables 5A to 12A show the calibration coefficients obtained for each gauge, at each temperature, and for both increasing and decreasing applied pressure. The coefficients were calculated by third-order linear regression of applied pressure, P_A, on frequency parameter, N. The number of calibration points used in the regression and the standard deviation of the residual errors are also listed in the tables. The coefficients are defined by the polynomial

$$P_A = B_0 + B_1N + B_2N^2 + B_3N^3 + e$$

where e is the residual error.

TABLE 5A

CALIBRATION COEFFICIENTS FOR GAUGE #372. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-378.582	.1639	-.0685	.1626	14	.0034
	5.0	-378.623	.1639	-.0686	.1627	14	.0039
	10.0	-378.743	.1639	-.0686	.1630	13	.0040
	15.0	-378.857	.1639	-.0686	.1628	14	.0039
	21.0	-378.564	.1636	-.0680	.1583	14	.0025
APPLIED PRESSURE DECRSING	.0	-378.633	.1639	-.0685	.1622	9	.0056
	5.0	-378.651	.1639	-.0684	.1614	9	.0052
	10.0	-378.913	.1640	-.0687	.1634	8	.0051
	15.0	-378.915	.1639	-.0685	.1616	8	.0048
	21.0	-379.096	.1640	-.0686	.1629	13	.0036

TABLE 6A

CALIBRATION COEFFICIENTS FOR GAUGE # 47. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-490.323	.1450	-.0572	.1185	14	.0044
	5.0	-490.664	.1452	-.0576	.1203	14	.0052
	10.0	-490.091	.1449	-.0572	.1184	14	.0049
	15.0	-489.988	.1449	-.0572	.1182	14	.0039
	20.5	-490.186	.1450	-.0573	.1194	14	.0060
APPLIED PRESSURE DECRSING	.0	-490.544	.1450	-.0573	.1185	8	.0065
	5.0	-490.844	.1452	-.0576	.1203	8	.0065
	10.0	-490.708	.1452	-.0575	.1199	8	.0046
	15.0	-490.330	.1450	-.0573	.1185	9	.0047
	20.5	-490.333	.1450	-.0572	.1183	8	.0048

TABLE 7A

CALIBRATION COEFFICIENTS FOR GAUGE #344. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-59.722	.2550	-.0733	-.1063	14	.0051
	5.0	-59.747	.2551	-.0739	-.0945	14	.0046
	10.0	-59.729	.2550	-.0736	-.1015	13	.0047
	15.0	-59.780	.2552	-.0750	-.0672	14	.0040
	21.0	-59.683	.2549	-.0728	-.1192	14	.0035
APPLIED PRESSURE DECRSING	.0	-59.715	.2549	-.0721	-.1400	8	.0022
	5.0	-59.704	.2548	-.0710	-.1747	9	.0062
	10.0	-59.739	.2549	-.0726	-.1267	8	.0073
	15.0	-59.741	.2549	-.0720	-.1488	8	.0045
	21.0	-59.758	.2550	-.0727	-.1257	13	.0034

TABLE 8A

CALIBRATION COEFFICIENTS FOR GAUGE # 65. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-482.212	.6100	-.1997	.0105	11	.0469
	5.0	-482.051	.6095	-.1960	-.0629	11	.0446
	10.0	-482.274	.6098	-.1980	-.0237	12	.0466
	15.0	-482.374	.6098	-.1971	-.0503	11	.0570
	21.0	-482.891	.6105	-.2009	.0179	10	.0449
APPLIED PRESSURE DECRSING	.0	-482.327	.6101	-.1995	-.0026	10	.0504
	5.0	-482.339	.6099	-.1981	-.0323	11	.0482
	10.0	-482.843	.6108	-.2030	.0600	10	.0513
	15.0	-482.717	.6103	-.1998	-.0123	13	.0478
	21.0	-483.032	.6107	-.2013	.0092	10	.0465

TABLE 9A

CALIBRATION COEFFICIENTS FOR GAUGE #350. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-258.595	.6163	-.1871	-.3401	10	.0390
	5.0	-258.760	.6165	-.1882	-.3134	13	.0400
	10.0	-258.828	.6167	-.1890	-.3093	11	.0408
	15.0	-258.862	.6166	-.1877	-.3578	10	.0444
	21.0	-258.878	.6165	-.1873	-.3616	11	.0462
APPLIED PRESSURE DECRSING	.0					10	
	5.0	-259.016	.6172	-.1938	-.1723	12	.0614
	10.0	-258.917	.6168	-.1903	-.2768	12	.0497
	15.0	-258.943	.6167	-.1882	-.3562	12	.0483
	21.0	-259.218	.6173	-.1919	-.2788	13	.0588

TABLE 10A

CALIBRATION COEFFICIENTS FOR GAUGE #282. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-503.308	.5750	-.1737	-.1754	10	.0414
	5.0	-503.161	.5748	-.1725	-.1942	13	.0433
	10.0	-503.281	.5749	-.1729	-.1942	11	.0467
	15.0	-503.514	.5753	-.1742	-.1754	10	.0453
	21.0	-503.221	.5747	-.1713	-.2261	11	.0493
APPLIED PRESSURE DECRSING	.0					10	
	5.0	-503.847	.5760	-.1797	-.0620	12	.0604
	10.0	-503.583	.5755	-.1766	-.1252	12	.0506
	15.0	-503.580	.5754	-.1748	-.1667	12	.0463
	21.0	-504.116	.5762	-.1789	-.1047	13	.0579

TABLE 11A

CALIBRATION COEFFICIENTS FOR GAUGE #109. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-111.804	.5895	-.1692	-.2298	11	.0498
	5.0	-111.720	.5894	-.1673	-.2955	11	.0474
	10.0	-111.701	.5896	-.1695	-.2259	12	.0469
	15.0	-111.651	.5895	-.1676	-.2932	11	.0594
	21.0	-111.684	.5898	-.1702	-.2220	10	.0504
APPLIED PRESSURE DECRSING	.0	-111.851	.5896	-.1702	-.2194	10	.0522
	5.0	-111.783	.5896	-.1694	-.2504	11	.0500
	10.0	-111.786	.5899	-.1716	-.1870	10	.0528
	15.0	-111.724	.5898	-.1701	-.2438	13	.0506
	21.0	-111.697	.5899	-.1698	-.2663	10	.0479

TABLE 12A

CALIBRATION COEFFICIENTS FOR GAUGE #191. ALSO SHOWN ARE THE NUMBER OF CAL. PNTS. USED IN REGRESSION AND THE STAND. DEV. OF RES. ERRORS.

METHOD	TEMP (DEG C)	CALIBRATION COEFFICIENT				NO OF SAMPLES	SD RES (PSI)
		B0	B1(E-02)	B2(E-08)	B3(E-15)		
APPLIED PRESSURE INCRSING	.0	-94.870	.6445	-.2199	.2093	10	.0506
	5.0	-94.870	.6447	-.2209	.2504	11	.0467
	10.0	-94.811	.6446	-.2187	.1473	11	.0452
	15.0	-94.828	.6447	-.2204	.2093	12	.0453
	21.0	-94.809	.6447	-.2195	.1533	11	.0492
APPLIED PRESSURE DECRSING	.0	-94.959	.6449	-.2228	.2906	11	.0482
	5.0	-94.875	.6447	-.2207	.2195	12	.0483
	10.0	-94.858	.6448	-.2207	.2101	12	.0461
	15.0	-94.928	.6452	-.2251	.3478	11	.0477
	21.0	-94.891	.6451	-.2234	.2764	13	.0550

APPENDIX 3

TEMPERATURE SENSITIVITY ESTIMATES

Tables 13A to 20A show values of temperature sensitivity, $\alpha = dP/dT$, as a function of pressure and temperature, estimated from calibration coefficients obtained (a) by increasing applied pressure and (b) by decreasing applied pressure. Estimates were made by increasing the frequency parameter, N, by increments over the maximum pressure range for each gauge and applying the formula

$$\alpha \left(N, \frac{P_i + P_{i+1}}{2}, \frac{T_i + T_{i+1}}{2}\right) = \frac{P_i - P_{i+1}}{T_{i+1} - T_i}$$

where P_i is the pressure estimated from the regression formula

$$P = \sum_{j=1}^{3} B_{ji} N^j$$

and the B_{ji} are regression coefficients derived from calibration at temperature T_i.

Since pressure changes only by several millibars over the range of temperature, it is represented in the tables only by the first value, $(P_1 + P_2)/2$.

Values for gauges #350 and #282 at 2.5°C (Tables 17A(b) and 18A(b), respectively) are omitted since sufficiently accurate regressions could not be obtained for these even after rejection of three outlying calibration points. Some error is suspected for this calibration run - both gauges having been calibrated together.

TABLE 13A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 372. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
268145	10.4	.44	1.48	1.65	1.55
279473	20.7	.45	1.48	1.65	1.64
290801	31.0	.46	1.48	1.66	1.67
302129	41.1	.47	1.48	1.66	1.72
313457	51.2	.48	1.48	1.67	1.76
324785	61.2	.49	1.49	1.67	1.79
336113	71.0	.50	1.49	1.68	1.82
347441	80.8	.51	1.49	1.69	1.84
358769	90.5	.53	1.49	1.69	1.86
370097	100.1	.54	1.50	1.70	1.87
381425	109.6	.56	1.50	1.71	1.88
392753	119.0	.58	1.50	1.72	1.88
404081	128.3	.59	1.51	1.73	1.88
415408	137.5	.61	1.51	1.74	1.88
426737	146.7	.63	1.51	1.75	1.87
438065	155.8	.65	1.52	1.76	1.87
449393	164.7	.67	1.52	1.77	1.86
460721	173.6	.69	1.52	1.78	1.85
472049	182.4	.71	1.52	1.79	1.84
483377	191.1	.74	1.53	1.81	1.83
494705	199.8	.76	1.53	1.82	1.82
506033	208.4	.78	1.53	1.84	1.81
517361	216.8	.81	1.53	1.85	1.80
528689	225.2	.83	1.53	1.87	1.79
540017	233.6	.86	1.54	1.89	1.79
551345	241.8	.89	1.54	1.91	1.79
562673	250.0	.91	1.54	1.93	1.79
574001	258.1	.94	1.54	1.95	1.79
585329	266.1	.97	1.54	1.97	1.80
596657	274.1	1.00	1.54	1.99	1.82

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
596657	274.1	1.00	1.52	2.00	1.76
585330	266.1	.99	1.53	1.99	1.76
574003	258.1	.99	1.53	1.99	1.76
562676	250.0	.98	1.52	1.98	1.76
551349	241.8	.98	1.52	1.98	1.76
540022	233.6	.98	1.51	1.98	1.76
528695	225.3	.98	1.51	1.98	1.76
517368	216.9	.98	1.50	1.99	1.7
506041	208.4	.98	1.49	1.99	1.7
494714	199.8	.98	1.48	2.00	1.74
483387	191.2	.99	1.46	2.01	1.73
472060	182.4	.99	1.45	2.01	1.72
460733	173.6	.99	1.44	2.02	1.70
449406	164.7	1.00	1.43	2.03	1.69
438079	155.8	1.00	1.41	2.03	1.68
426753	146.7	1.00	1.40	2.04	1.67
415426	137.6	1.01	1.39	2.05	1.65
404099	128.3	1.01	1.38	2.05	1.64
392772	119.0	1.02	1.37	2.06	1.63
381445	109.6	1.02	1.36	2.06	1.62
370118	100.1	1.02	1.36	2.07	1.60
358791	90.5	1.02	1.35	2.07	1.59
347464	80.8	1.02	1.35	2.07	1.58
336137	71.1	1.02	1.35	2.06	1.57
324810	61.2	1.02	1.36	2.06	1.56
313483	51.2	1.02	1.36	2.05	1.55
302156	41.2	1.02	1.37	2.04	1.54
290829	31.0	1.02	1.39	2.02	1.52
279502	20.7	1.01	1.40	2.01	1.52
268176	10.4	1.01	1.43	1.99	1.52

(b)

TABLE 14A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 47. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	17.75
408622	10.2	-.84	-.81	-.35	.70
423306	20.9	-.87	-.74	-.33	.71
437991	31.6	-.90	-.67	-.31	.72
452675	42.2	-.92	-.62	-.29	.73
467360	52.2	-.93	-.57	-.27	.75
482044	62.4	-.94	-.52	-.26	.77
496729	72.5	-.94	-.49	-.24	.79
511413	82.4	-.94	-.45	-.23	.81
526098	92.2	-.93	-.43	-.21	.83
540782	101.9	-.92	-.40	-.20	.85
555467	111.5	-.90	-.38	-.19	.87
570151	121.0	-.89	-.37	-.18	.90
584836	130.4	-.87	-.36	-.17	.92
599520	139.6	-.85	-.35	-.16	.94
614205	148.8	-.82	-.34	-.15	.96
628889	157.8	-.80	-.33	-.14	.98
643574	166.7	-.78	-.32	-.13	1.00
658258	175.6	-.75	-.31	-.12	1.02
672943	184.3	-.73	-.31	-.11	1.04
687627	192.9	-.70	-.31	-.10	1.05
702312	201.4	-.68	-.30	-.10	1.06
716996	209.9	-.66	-.29	-.09	1.07
731681	218.2	-.64	-.28	-.09	1.07
746365	226.4	-.63	-.28	-.08	1.08
761050	234.6	-.62	-.25	-.07	1.07
775734	242.9	-.61	-.22	-.07	1.07
790419	250.6	-.60	-.20	-.06	1.06
805103	258.5	-.61	-.17	-.06	1.05
819788	266.3	-.61	-.13	-.05	1.03
834473	274.0	-.62	-.09	-.05	1.00

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	17.75
834473	274.0	-.62	-.08	-.07	1.06
819789	266.3	-.58	-.11	-.10	1.05
805105	258.5	-.56	-.14	-.12	1.04
790421	250.6	-.54	-.17	-.14	1.03
775738	242.7	-.53	-.20	-.16	1.02
761053	234.6	-.52	-.22	-.17	1.01
746369	226.5	-.52	-.24	-.18	1.00
731685	218.2	-.53	-.27	-.18	.99
717001	209.9	-.53	-.29	-.19	.99
702317	201.5	-.55	-.31	-.19	.98
687633	192.9	-.56	-.32	-.19	.98
672949	184.3	-.58	-.34	-.19	.97
658265	175.6	-.60	-.36	-.19	.96
643580	166.8	-.62	-.37	-.19	.96
628897	157.8	-.64	-.39	-.19	.95
614214	148.8	-.67	-.40	-.19	.95
599530	139.6	-.69	-.42	-.19	.94
584846	130.4	-.71	-.43	-.19	.94
570162	121.0	-.74	-.44	-.19	.93
555478	111.5	-.76	-.45	-.20	.93
540794	101.9	-.78	-.45	-.20	.94
526110	92.2	-.80	-.48	-.22	.94
511426	82.4	-.81	-.49	-.22	.93
496742	72.5	-.82	-.50	-.24	.90
482058	62.4	-.83	-.52	-.26	.89
467374	52.2	-.84	-.53	-.28	.88
452690	41.9	-.84	-.55	-.31	.88
438006	31.5	-.83	-.52	-.34	.87
423322	20.9	-.82	-.48	-.38	.86
408639	10.2	-.80	-.60	-.43	.85

(b)

TABLE 15A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 344. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
28263	10.2	.08	-.13	.21	-.35
34780	19.7	.04	-.11	.14	-.24
40197	29.4	.01	-.10	.09	-.14
45614	38.7	-.02	-.09	.04	-.06
51031	48.2	-.05	-.08	.01	.02
56448	57.6	-.07	-.07	-.03	.08
61865	66.9	-.09	-.06	-.05	.14
67282	76.3	-.11	-.06	-.07	.18
72699	85.6	-.12	-.05	-.08	.22
78116	94.9	-.14	-.05	-.09	.25
83533	104.1	-.14	-.04	-.09	.28
88950	113.4	-.15	-.04	-.09	.30
94367	122.5	-.15	-.04	-.08	.31
99784	131.7	-.16	-.04	-.07	.32
105201	140.8	-.16	-.04	-.06	.33
110619	149.9	-.15	-.04	-.05	.33
116036	159.0	-.15	-.04	-.03	.32
121453	168.0	-.15	-.04	-.01	.32
126870	177.0	-.14	-.04	.01	.31
132287	186.0	-.13	-.04	.03	.30
137704	194.9	-.12	-.04	.05	.29
143121	203.8	-.12	-.04	.07	.28
148538	212.6	-.11	-.04	.09	.27
153955	221.5	-.10	-.04	.11	.26
159372	230.4	-.08	-.04	.13	.26
164789	239.1	-.07	-.04	.14	.25
170206	247.9	-.06	-.04	.16	.25
175623	256.6	-.05	-.03	.17	.25
181040	265.3	-.04	-.03	.17	.25
186457	273.9	-.03	-.03	.17	.26

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
186458	273.9	.00	-.06	.16	.27
181041	265.3	-.04	-.02	.13	.29
175624	256.6	-.07	.02	.10	.31
170207	247.9	-.10	.04	.08	.32
164790	239.1	-.12	.06	.06	.32
159374	230.4	-.13	.08	.04	.33
153957	221.5	-.14	.08	.03	.33
148540	212.7	-.14	.08	.03	.33
143123	203.8	-.14	.08	.02	.32
137706	194.9	-.13	.07	.02	.31
132290	186.0	-.13	.06	.02	.31
126873	177.0	-.12	.05	.02	.30
121456	168.0	-.10	.03	.03	.28
116039	159.0	-.09	.02	.04	.27
110622	149.9	-.07	.00	.05	.26
105206	140.8	-.05	-.02	.06	.24
99789	131.7	-.03	-.04	.07	.23
94372	122.5	-.01	-.06	.08	.21
88955	113.3	.01	-.07	.09	.20
83538	104.1	.02	-.08	.10	.18
78122	94.9	.04	-.09	.11	.17
72705	85.6	.05	-.10	.12	.16
67288	76.3	.07	-.10	.13	.14
61871	66.9	.08	-.10	.14	.13
56454	57.5	.08	-.09	.14	.13
51038	48.1	.09	-.08	.15	.12
45621	38.7	.09	-.05	.15	.11
40204	29.4	.08	-.03	.15	.11
34787	19.7	.07	.01	.14	.11
29371	10.2	.05	.06	.14	.12

(b)

TABLE 16A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 65. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
83839	10.6	.92	.75	1.18	1.62
89438	33.3	.96	.68	1.13	1.48
95038	55.9	.99	.62	1.08	1.35
100638	78.3	1.01	.57	1.03	1.24
106238	100.7	1.01	.52	.97	1.14
111838	123.0	1.00	.48	.92	1.05
117437	145.3	.98	.45	.87	.98
123037	167.4	.95	.42	.81	.91
128637	189.4	.92	.40	.76	.86
134237	211.4	.87	.38	.70	.81
139837	233.2	.82	.36	.65	.77
145437	255.0	.76	.35	.60	.74
151036	276.7	.70	.34	.55	.72
156636	298.3	.64	.33	.51	.70
162236	319.8	.58	.32	.46	.68
167836	341.3	.51	.32	.42	.67
173436	362.6	.45	.31	.39	.66
179036	383.8	.38	.30	.35	.66
184635	405.0	.32	.30	.33	.65
190235	426.1	.26	.29	.30	.65
195835	447.1	.21	.27	.28	.64
201435	468.0	.16	.26	.27	.64
207035	488.8	.12	.24	.26	.63
212635	509.5	.09	.22	.26	.63
218234	530.1	.06	.19	.27	.62
223834	550.7	.05	.16	.28	.60
229434	571.1	.05	.12	.30	.58
235034	591.5	.06	.08	.33	.56
240634	611.8	.08	.03	.37	.53
246233	632.0	.12	-.03	.42	.49

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
246234	632.0	.19	-.04	.34	.67
240632	611.8	.18	.04	.24	.65
235031	591.5	.17	.12	.17	.64
229430	571.1	.17	.17	.11	.62
223829	550.7	.18	.22	.02	.61
218227	530.1	.19	.25	.06	.59
212626	509.5	.21	.28	.03	.58
207025	488.8	.24	.29	.01	.57
201424	467.9	.26	.30	.00	.56
195823	447.0	.29	.30	.00	.55
190221	426.0	.33	.30	.02	.55
184620	405.0	.36	.29	.04	.55
179019	383.8	.40	.28	.07	.55
173418	362.5	.44	.27	.10	.55
167817	341.2	.48	.26	.14	.55
162215	319.8	.52	.25	.19	.56
156614	298.2	.57	.25	.23	.57
151013	276.6	.61	.25	.28	.59
145412	254.9	.65	.26	.33	.61
139811	233.1	.69	.26	.39	.63
134209	211.3	.73	.27	.44	.66
128608	189.3	.77	.30	.48	.69
123007	167.3	.81	.33	.53	.73
117406	145.1	.84	.38	.57	.78
111805	122.9	.87	.44	.60	.83
106203	100.6	.90	.51	.63	.89
100602	78.2	.92	.60	.65	.95
95001	55.7	.94	.71	.67	1.02
89400	33.1	.95	.83	.67	1.10
83799	10.5	.96	.98	.66	1.18
			1.14	.64	1.27

(b)

TABLE 17A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 350. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
45068	10.7	1.24	.12	.71	.23
50427	17.1	1.14	.05	.68	.25
55787	25.7	1.04	-.02	.63	.27
61146	78.1	.96	-.08	.59	.29
66506	100.4	.87	-.13	.54	.31
71865	122.7	.79	-.18	.48	.32
77225	144.8	.72	-.23	.43	.33
82584	166.9	.65	-.26	.37	.34
87944	188.9	.58	-.30	.31	.35
93303	210.8	.51	-.32	.26	.35
98663	232.6	.45	-.34	.20	.36
104023	254.4	.39	-.36	.14	.36
109382	276.1	.33	-.37	.09	.36
114742	297.7	.27	-.37	.04	.36
120101	319.2	.21	-.37	-.02	.35
125461	340.6	.16	-.37	-.06	.35
130820	362.0	.10	-.36	-.10	.34
136180	383.2	.04	-.34	-.14	.33
141539	404.4	-.02	-.32	-.17	.32
146899	425.5	-.07	-.30	-.20	.31
152259	446.5	-.13	-.27	-.22	.30
157618	467.5	-.19	-.23	-.23	.28
162978	488.4	-.26	-.19	-.23	.26
168337	509.2	-.32	-.14	-.23	.25
173697	529.9	-.39	-.10	-.21	.23
179056	550.5	-.45	-.04	-.19	.21
184416	571.0	-.53	.02	-.16	.18
189775	591.5	-.60	.08	-.11	.16
195135	611.8	-.68	.15	-.05	.14
200494	632.1	-.77	.22	.02	.11

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
200495	631.5		.16	.23	.19
195134	612.2		.03	.09	.18
189773	592.6		-.09	.04	.17
184412	572.9		-.18	-.05	.16
179052	553.1		-.26	-.13	.14
173691	533.2		-.32	-.21	.12
168330	513.2		-.36	-.26	.10
162969	493.1		-.39	-.32	.07
157609	472.9		-.41	-.40	.05
152248	452.7		-.41	-.43	.03
146887	432.4		-.41	-.44	.00
141527	412.1		-.39	-.44	-.01
136166	391.7		-.37	-.43	-.03
130805	371.3		-.34	-.41	-.04
125444	350.9		-.31	-.38	-.05
120084	330.4		-.27	-.34	-.05
114723	309.9		-.23	-.29	-.05
109362	289.4		-.19	-.24	-.04
104001	268.9		-.15	-.18	-.03
98641	248.3		-.11	-.12	-.01
93280	227.8		-.08	-.06	.02
87919	207.2		-.05	.00	.06
82559	186.7		-.02	.07	.12
77198	166.2		.00	.14	.18
71837	145.7		.01	.20	.25
66476	125.3		.00	.26	.34
61116	104.9		-.01	.32	.44
55755	84.6		-.03	.38	.56
50394	64.5		-.07	.44	.69
45034	44.7		-.13	.47	.84
	25.3			.50	1.01

(b)

TABLE 18A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 282. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
92787	10.6	-.45	.03	.50	-.12
98752	33.3	-.42	-.04	.40	-.05
104717	55.9	-.40	-.11	.31	.01
110683	78.5	-.38	-.17	.22	.07
116648	100.9	-.37	-.22	.14	.11
122613	123.2	-.37	-.28	.07	.14
128579	145.5	-.37	-.32	.00	.15
134544	167.7	-.38	-.36	-.06	.17
140510	189.7	-.40	-.40	-.11	.18
146475	211.7	-.42	-.44	-.16	.18
152440	233.6	-.44	-.46	-.21	.17
158406	255.4	-.47	-.49	-.25	.16
164371	277.1	-.50	-.51	-.28	.14
170336	298.7	-.53	-.52	-.31	.12
176302	320.2	-.57	-.54	-.34	.10
182267	341.6	-.61	-.54	-.37	.07
188233	363.0	-.65	-.54	-.39	.04
194198	384.3	-.70	-.54	-.41	.01
200163	405.4	-.75	-.53	-.43	-.02
206129	426.5	-.79	-.52	-.45	-.04
212094	447.5	-.84	-.51	-.46	-.07
218059	468.3	-.89	-.48	-.48	-.09
224025	489.1	-.94	-.46	-.49	-.11
229990	509.8	-1.00	-.43	-.50	-.13
235956	530.4	-1.05	-.40	-.52	-.14
241921	550.9	-1.10	-.36	-.53	-.15
247886	571.4	-1.14	-.34	-.55	-.15
253852	591.7	-1.19	-.27	-.56	-.15
259817	611.9	-1.24	-.21	-.58	-.14
265782	632.0	-1.28	-.16	-.59	-.12

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
265783	631.9		-.13	-.35	-.15
259816	612.1		-.24	-.47	-.13
253849	592.1		-.33	-.57	-.13
247883	572.0		-.41	-.66	-.13
241916	551.8		-.47	-.73	-.14
235949	531.5		-.52	-.78	-.13
229983	511.3		-.53	-.82	-.16
224016	491.4		-.57	-.85	-.18
218050	471.5		-.58	-.87	-.20
212083	451.4		-.58	-.88	-.22
206116	431.3		-.58	-.87	-.24
200150	411.0		-.56	-.85	-.26
194183	390.7		-.54	-.83	-.28
188216	370.4		-.52	-.80	-.30
182250	349.9		-.49	-.76	-.31
176283	329.5		-.46	-.71	-.33
170317	308.9		-.43	-.66	-.34
164350	288.4		-.39	-.60	-.36
158383	267.7		-.35	-.54	-.37
152417	247.0		-.33	-.48	-.37
146450	226.2		-.30	-.41	-.37
140483	205.3		-.28	-.34	-.37
134517	184.3		-.26	-.27	-.37
128550	163.2		-.25	-.20	-.36
122584	142.1		-.25	-.12	-.35
116617	120.8		-.25	-.04	-.33
110650	99.4		-.26	.01	-.32
104684	77.8		-.29	.08	-.30
98717	56.1		-.33	.14	-.30
92751	34.2		-.38	.20	-.28

(b)

TABLE 19A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 109. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
21613	10.4	-.93	-.85	-.49	-.25
27110	32.9	-.91	-.95	-.47	-.37
32607	55.3	-.89	-1.05	-.46	-.48
38105	77.6	-.89	-1.13	-.45	-.57
43602	99.8	-.90	-1.19	-.46	-.65
49099	122.0	-.91	-1.25	-.48	-.72
54597	144.1	-.94	-1.30	-.50	-.78
60094	166.1	-.97	-1.33	-.54	-.83
65592	188.1	-1.01	-1.36	-.57	-.87
71089	210.0	-1.06	-1.38	-.62	-.90
76586	231.8	-1.11	-1.40	-.66	-.93
82084	253.5	-1.16	-1.41	-.71	-.94
87581	275.2	-1.22	-1.41	-.77	-.95
93078	296.8	-1.28	-1.41	-.82	-.96
98576	318.3	-1.34	-1.41	-.87	-.96
104073	339.7	-1.41	-1.41	-.93	-.96
109571	361.0	-1.47	-1.40	-.98	-.95
115068	382.3	-1.53	-1.40	-1.03	-.95
120565	403.5	-1.59	-1.40	-1.07	-.94
126063	424.7	-1.64	-1.40	-1.11	-.93
131560	445.7	-1.69	-1.40	-1.15	-.93
137057	466.7	-1.74	-1.41	-1.18	-.92
142555	487.6	-1.78	-1.43	-1.20	-.92
148052	508.4	-1.81	-1.45	-1.21	-.92
153550	529.2	-1.84	-1.47	-1.22	-.93
159047	549.9	-1.85	-1.51	-1.21	-.93
164544	570.5	-1.86	-1.55	-1.20	-.95
170042	591.0	-1.85	-1.61	-1.17	-.97
175539	611.4	-1.84	-1.67	-1.13	-1.00
181036	631.8	-1.81	-1.75	-1.07	-1.04

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
181037	631.8	-1.65	-1.79	-1.13	-.85
175538	611.4	-1.66	-1.73	-1.19	-.89
170039	591.0	-1.67	-1.69	-1.23	-.93
164540	570.5	-1.67	-1.65	-1.27	-.96
159041	549.9	-1.67	-1.62	-1.29	-.99
153543	529.2	-1.66	-1.59	-1.30	-1.01
148044	508.4	-1.64	-1.58	-1.31	-1.02
142545	487.6	-1.62	-1.56	-1.30	-1.03
137046	466.7	-1.60	-1.55	-1.29	-1.03
131548	445.7	-1.57	-1.55	-1.27	-1.03
126049	424.6	-1.54	-1.54	-1.25	-1.03
120550	403.5	-1.51	-1.54	-1.22	-1.02
115051	382.3	-1.47	-1.53	-1.18	-1.01
109553	361.0	-1.44	-1.53	-1.15	-.99
104054	339.6	-1.40	-1.52	-1.11	-.97
98555	318.2	-1.36	-1.52	-1.06	-.95
93056	296.7	-1.32	-1.50	-1.02	-.92
87558	275.1	-1.28	-1.49	-.98	-.90
82059	253.4	-1.24	-1.47	-.93	-.87
76560	231.7	-1.20	-1.44	-.89	-.83
71061	209.9	-1.16	-1.41	-.85	-.80
65563	188.0	-1.12	-1.36	-.81	-.76
60064	166.0	-1.09	-1.31	-.78	-.73
54565	144.0	-1.05	-1.25	-.75	-.69
49066	121.9	-1.02	-1.18	-.72	-.65
43568	99.7	-1.00	-1.10	-.71	-.64
38069	77.5	-.98	-1.01	-.70	-.57
32570	55.1	-.96	-.90	-.69	-.54
27071	32.7	-.94	-.78	-.70	-.50
21573	10.3	-.94	-.65	-.71	-.46

(b)

TABLE 20A

TABLE OF DP/DT IN MBAR/DEG C VERSUS TEMPERATURE AND PRESSURE FOR GAUGE # 191. N IS THE FREQUENCY COUNT VALUE FROM WHICH PRESSURE IS DERIVED.

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
17149	10.6	-.22	-.71	-.07	-.29
22181	33.1	-.28	-.71	-.14	-.32
27213	55.5	-.32	-.71	-.19	-.35
32246	77.8	-.37	-.72	-.24	-.39
37278	100.1	-.40	-.74	-.28	-.42
42310	122.3	-.44	-.77	-.32	-.46
47343	144.4	-.47	-.81	-.34	-.51
52375	166.4	-.49	-.85	-.36	-.55
57408	188.4	-.52	-.89	-.37	-.59
62440	210.3	-.54	-.94	-.38	-.63
67472	232.1	-.56	-.99	-.39	-.67
72505	253.8	-.58	-1.04	-.39	-.71
77537	275.5	-.60	-1.09	-.39	-.75
82569	297.0	-.62	-1.14	-.39	-.79
87602	318.5	-.64	-1.19	-.38	-.82
92634	340.0	-.66	-1.23	-.37	-.85
97667	361.3	-.67	-1.27	-.37	-.88
102699	382.6	-.70	-1.30	-.36	-.90
107731	403.8	-.72	-1.32	-.36	-.92
112764	424.9	-.74	-1.34	-.35	-.93
117796	445.9	-.77	-1.35	-.35	-.93
122828	466.9	-.80	-1.35	-.36	-.93
127861	487.8	-.84	-1.33	-.36	-.93
132893	508.6	-.87	-1.30	-.37	-.91
137926	529.3	-.92	-1.26	-.39	-.89
142958	550.0	-.96	-1.21	-.41	-.86
147990	570.6	-1.02	-1.14	-.44	-.82
153023	591.1	-1.07	-1.05	-.48	-.77
158055	611.6	-1.14	-.94	-.52	-.72
163087	631.9	-1.21	-.82	-.57	-.65

(a)

N	PRESS (DBAR)	TEMPERATURE (DEG C)			
		2.50	7.50	12.50	18.00
163088	631.9	-1.16	-.91	-.59	-.68
158053	611.5	-1.19	-.91	-.54	-.73
153019	591.1	-1.21	-.92	-.51	-.77
147985	570.6	-1.22	-.92	-.50	-.79
142951	550.0	-1.22	-.92	-.49	-.81
137917	529.3	-1.22	-.91	-.50	-.82
132883	508.6	-1.21	-.91	-.51	-.82
127849	487.7	-1.19	-.90	-.54	-.82
122815	466.9	-1.17	-.89	-.56	-.81
117781	445.9	-1.14	-.87	-.60	-.80
112747	424.8	-1.11	-.86	-.63	-.78
107713	403.7	-1.08	-.84	-.67	-.75
102679	382.5	-1.05	-.82	-.70	-.72
97645	361.2	-1.01	-.81	-.74	-.69
92611	339.9	-.97	-.78	-.77	-.66
87576	318.4	-.94	-.76	-.80	-.63
82542	296.9	-.90	-.74	-.82	-.59
77508	275.4	-.87	-.71	-.83	-.56
72474	253.7	-.84	-.69	-.84	-.52
67440	232.0	-.82	-.66	-.83	-.49
62406	210.2	-.79	-.63	-.81	-.45
57372	188.3	-.78	-.60	-.78	-.42
52338	166.3	-.77	-.57	-.74	-.40
47304	144.2	-.76	-.54	-.67	-.37
42270	122.1	-.76	-.51	-.59	-.35
37236	99.9	-.78	-.48	-.49	-.34
32202	77.6	-.79	-.45	-.37	-.33
27168	55.3	-.82	-.41	-.23	-.33
22134	32.8	-.86	-.38	-.06	-.33
17100	10.3	-.91	-.35	.13	-.34

(b)

APPENDIX 4

DERIVATION OF TEMPERATURE SENSITIVITY

To derive an expression for temperature sensitivity we first note that the apparent pressure, that is, the pressure as measured by the gauge using expression (2) of Subsection 2.2, can be written as a function of the crystal frequency parameter, N, as

$$\hat{P} = \hat{P}\,(N\,(P,T,t))$$

where the true applied pressure, P, and temperature, T, are also functions of time t. The temperature sensitivity of the gauge is then defined by

$$\alpha = \frac{d\hat{P}}{dT} = \frac{\partial \hat{P}}{\partial N}\frac{\partial N}{\partial T} \tag{1A}$$

Estimating the partial derivative, $\partial N/\partial T$, using the Taylor expansion for small changes in N

$$\Delta N = \frac{\partial N}{\partial P}\Delta P + \frac{\partial N}{\partial T}\Delta T + O(\Delta T^2, \Delta P^2, \Delta T \Delta P, \Delta t) \tag{2A}$$

gives

$$\frac{\partial N}{\partial T} = \frac{\Delta N}{\Delta T} - \frac{\partial N}{\partial P}\frac{\Delta P}{\Delta T} \tag{3A}$$

and (1A) becomes

$$\alpha = \frac{\partial \hat{P}}{\partial N}\frac{\Delta N}{\Delta T} - \frac{\Delta P}{\Delta T} \tag{4A}$$

where the approximation

$$\frac{\partial \hat{P}}{\partial N}\frac{\partial N}{\partial P} = \frac{\partial \hat{P}}{\partial P} = 1$$

has been made.

When estimating α by holding applied pressure constant, the term $\Delta P/\Delta T$ in (4A) is the correction term to apply due to variations in atmospheric pressure and the factor $\partial \hat{P}/\partial N$ is taken from a calibration at constant temperature. When estimating α by fixing N, as carried out in Subsection 3.1, (4A) reduces to

$$\alpha = -\frac{\Delta P}{\Delta T} \qquad (5A)$$